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THE DEVELOPMENT OF 'ECO-FRIENDLY' CONCRETE USING SILICA FUME WITH HIGH ECONOMIC VALUES

by

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THE DEVELOPMENT OF 'ECO-FRIENDLY' CONCRETE USING SILICA FUME WITH HIGH ECONOMIC VALUES

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FOONG KAH YEN

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DEDICATIONS

This Thesis is Dedicated

To

My Beloved Family, My Supervisor and Dear Friends

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ABSTRACT

The world's yearly cement production of 2 billion tons emits about 7% of carbon dioxide (CO_2) into the atmosphere. Producing a ton of Ordinary Portland Cement (OPC) produces a ton of CO_2. In concrete production, OPC should not only be considered as the main high strength contributor. Aggregate gradings and types of admixtures should be taken into serious consideration. Major concrete issues such as pre-structural deterioration, durability in marine environment and natural resources depletion should be concerned. Silica Fume (SF), the by-products of metal industries attracts the attention of many parties. SF abundance availability has become an environmental issue but being a potential high strength contributor has attracted many parties into applying its application into the concrete technology and construction industry. This research is to produce concrete that is high performance and high strength from 50MPa-80MPa having the 'Eco-Green' characteristics. The research was conducted using the Trial Laboratory Test method. X-Ray Diffraction (XRD) and X-Ray Fluorescence (XRF) analyses were conducted to analyze the chemical compositions of OPC and SF. SF is then added 5% and 10% into 2 types of aggregate mixes namely 'Designed' and 'As-supplied' with fixed 0.5w/c. Excel worksheets were produced to determine the cement efficiency and cost effectiveness. It is concluded that by adding SF, the strength of concrete has increase by 15%-20%. With comparisons from other research, cement consumption is reduced by 15%-20%. CO_2 emissions were reduced by 15%-20%, energy efficient during production and have enhanced durability. This can be justified from Excel worksheets produced. OPC content is not the main contributor to the high strength of concrete. This is part of an effort to produce the ideal building material that delivers many positive traits.

Keywords: Carbon Dioxide (CO_2); 'eco-green'; Ordinary Portland cement (OPC); Silica Fume (SF); Trial Laboratory Test; X-Ray Diffraction (XRD)

ABSTRAK

Produksi tahunan simen sebanyak 2 billion ton dibuktikan membebaskan 7% gas karbon dioksida ke atmosfera. Satu ton simen yang dihasilkan akan membebaskan satu ton gas karbon dioksida. Dalam produksi konkrit, simen tidak harus dijadikan tumpuan utama untuk mencapai kekuatan tinggi. Keseimbangan kandungan aggregate dan jenis bahan kimia harus dititikberatkan. Isu-isu utama konkrit misalnya kerosakan pra-struktur, daya tahanan dalam kawasan pesisir dan kemerosotan sumber alam juga harus diutamakan. Silica Fume (SF) hasil sampingan industry pengilangan aloi telah menarik perhatian pelbagai pihak. Hasilnya yang banyak telah menjadi tumpuan isu persekitaran tetapi jika dipandang dari ciri-cirinya untuk menghasilkan konkrit berkekuatan tinggi telah menarik minat pelbagai pihak untuk diaplikasikan dalam teknologi konkrit dan pembinaan. Objektif utama penyelidikan ini adalah untuk menghasilkan konkrit yang berprestasi dan berkekuatan tinggi dalam lingkungan kuatan 50MPa-80MPa dengan ciri-ciri 'Eco-Green'. Kaedah ujian 'Trial Laboratory' telah digunakan. Ujian belauan sinar-x dan analisis pendarkilau sinar-x dijalankan untuk menganalisa komposisi kimia simen dan SF yang telah ditambahkan 5% dan 10% dalam dua jenis campuran konkrit iaitu 'Designed' dan 'As-supplied' dengan nisbah air simen tetap 0.5. Program computer asas telah dihasilkan dan digunakan untuk menentukan jumlah kepenggunaan simen dan kos. Kesimpulannya, dengan penambahan SF, kekuatan konkrit telah meningkat sebanyak 15%-20%. Dengan perbandingan penyelidikan, kandungan guna simen telah dikurangkan sebanyak 15%-20% selaras dengan kadar pembebasan gas karbon dioksida. Konkrit yang dihasilkan adalah berpatutan dan menjimtkan tenaga semasa produksi dengan adanya daya tahan yang baik dalam keadaan pedalaman dan persisir. Oleh itu kandungan simen dalam konkrit bukan fokus utama kekuatan tinggi dalam konkrit berkualiti tinggi. Penyelidikan ini adalah sebahagian usaha untuk menghasilkan bahan binaan yang ideal dan berpotensi.

Kata kunci: karbon dioksida; daya tahanan; 'eko-hijau'; beton prestasi tinggi; simen; Silica Fume (SF)

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LIST OF ABBREVIATIONS

OPC	Ordinary Portland cement
HPC	High Performance Concrete
HCP	Hydrated Cement Paste
SF	Silica Fume
w/c	Water to cement ratio
w/b	Water to binder ratio
CA	Coarse Aggregates
CO_2	Carbon Dioxide
FA	Fine Aggregates
SP	Superplasticizer
XRF	X-Ray Florescence
XRD	X-Ray Diffraction
SEM	Scanning Electron Microscopy
FESEM	Field Emission Scanning Electron Microscopy
etc	Et cetera
i.e.	In example
PCC	Portland Cement Concrete
SFC	Silica Fume Concrete
UD	'Undesigned'/ 'As-supplied' Mixes
CRM	Cement Replacing Material

CHAPTER 1: INTRODUCTION

1.1 Background

In the modern world, concrete is the second largest consumable material after water. From material process, mixing and proportioning, delivery, placement and finishing sustainability of concrete is regarded as an 'eco-green' material. It is a matter of fact that the sustainability and ecological balance in the concrete production is more important than the unit price of concrete. The concrete industry of tomorrow will have to continue to produce a commodity product and also niche concretes with high added value (V.M. Malhotra and K.P. Mehta, 2004).

Among all the materials used in making concrete, cement production emits the highest amount of carbon dioxide (CO_2) gas into the environment. Cement contributes about 15% weight in the total production of nearly 5 billion ton/year.

In 2004, global CO_2 emissions from cement production were reported as 298 million metric tons which is 3.8% of the global CO_2 emission. The amounts of CO_2 embodied in concrete are primarily a function of the cement content in the mix designs. It is important to note that structures are built with concrete and not with cement. A portion of the CO_2 produced during manufacturing of cement is reabsorbed into concrete during the product life-cycle through a process called carbonation. Study estimates that between 33% and 57% of the CO_2 emitted from calcinations will be reabsorbed through carbonation of concrete surfaces over a 100 year life cycle. In 2005, China and India tops the cement manufacturing market followed by the US producing as total of 2300 million tons of cement annually (G.N. Edward *et.al*, 2003)

In view of the need for optimum use of cement in concrete; since last two decades, huge efforts were made to enhance the performance of concrete that involves better compaction, enhanced paste characteristics, and perfect bond between aggregate-matrix and reduced porosity. In these systems, a substantial reduction in water-to-cement ratio is achieved through the use of super-plasticizers; further enhancements of some properties have been obtained through the addition of mineral micro-fillers (supplementary cementitious or pozzolanic materials such as silica fume and fly-ash) and recycled concrete wastes from construction structures demolitions (M.D. Luther and P.A. Smith, 1991; Federal Highway Association, 2008; V.M. Malhotra and K.P. Mehta, 2004)

High Performance Concrete (HPC) is a specialized series of concrete that is designed to provide several benefits in the construction of structures that cannot always be achieved routinely using the conventional ingredients, normal mixing and curing practices. In simple manner, HPC is produced where certain characteristics are developed for a particular application and environment so that it can give excellent performance in the structure in which it is to be placed, the environment in which it is to be exposed and with the loads that is supposed to be encountered during its design life. An example of a characteristic that may be considered critical in an application requiring performance is the early age strength. Concretes possessing this characteristic often achieve higher strength. Therefore, HPC is often of high strength, but high strength concrete may not necessarily be the high performance. Traditionally, interests in the strength of concrete have been focused on those at the age of 28 days and beyond (M.L. Gambhir, 2005; A.M. Neville, 1998 and M. Ali, 1996).

Besides having huge favor in the urban mainland constructions, the marine environment is also given great attention. In tropical countries such as Malaysia, the chloride content in sea waters is said to be drastically increasing annually by 3% due to increased temperature and salinity concentrations. This phenomenon mainly happens at concrete jetty structures and platforms. To what is known, reinforced concrete is usually durable and cost effective which causes the widespread use for the construction of concrete structures. However, it has become increasingly apparent that the attack by aggressive agents such as chloride ions, leading to corrosion of embedded steel, causes a structure to deteriorate. Thus, the corrosion of reinforcing steel in concrete due to chloride transport in concrete structures in a marine environment has received increasing attention in recent years because of its widespread occurrence and the high cost of repair. Thus, it is important to know how much can this ion penetrate HPC and how durable HPC is to this aggressive chemical. This can be done by measuring the depth penetration of salt water in samples. To prevent chloride permeation into concrete, finely grained materials are used where it has been investigated and proven to be successful (K. Chong and R. Larrard, 1996).

Currently it is a major concern to achieve sustainable construction. Building and structures enabled mankind to meet their social needs for shelter, economically for investment and to achieve corporate objectives. However, the satisfaction of these needs usually comes with high price for example an irreversible damage to our environment. This leads to a growing realization around the world to alter or to improve our conventional way of development into a more responsible approach which can satisfy our needs for development without harming the world that we are living in. An opportunity sparked when a new philosophy called 'sustainable development' was introduced in 1987 in the Bruntland Report. Since then, many progressive world events had taken place to increase the awareness on environment and sustainability agendas such as Rio Earth Summit 1992, Maastricht Treaty 1992, Kyoto Protocol on Global Warming 1997, Johannesburg Earth Summit 2002 and Washington Earth Observation Summit 2003. Through sustainable construction concept, the construction industry can contribute in a positive way and proactive manner towards environmental protection (M.F.M. Zain *et.al*, 2005).

Delivering sustainable construction requires action from all engaged from constructing to maintaining the structure or building. This includes providing design, consulting and construction services (W. Atkins, 2001). It requires exploration to new territories in construction approach and prepares to adopt new products, ideas and practices. As global interest on sustainability starts to bloom, Malaysia should not be left out in triumphing on sustainability and sustainable construction. Malaysia needs to express herself so to abide by this new interest to compete in the global market (G. Ofori *et.al*, 2000).

In Malaysia, to achieve sustainability in construction. Construction industry must inevitably change its historic methods of operating with little regard for environmental impacts to a new mode that makes environmental concerns a centerpiece of its efforts. Previously, the concern on environment is relatively a small part of most of construction development. However with the growing awareness on environmental protection due to the depletion of natural resources, global warming and extremity of destruction to ecology and biodiversity impact, these issues have gain wider attention by practicing engineers worldwide. The direction of the construction industry is now shifting from developing with environmental concern as a small part of the process being integrated within the wider context of environment agenda. Thus, the activities of construction industry must work and comply with the needs to protect and sustain the environment.

Sustainable construction, which has been dubbed 'green construction', describes the responsibility of the industry in attaining sustainability. The term sustainability has been adopted as a panacea for change and development (C. Hayles, 2004)

1.2 Problem Statement.

One of the most serious problems in the production of huge quantity of concrete is the large amount of CO_2 emission and energy consumption during concrete production. About 7% of CO_2, is generated worldwide through concrete production. Resource productivity considerations will require minimizing Portland cement use to meet the future demands of eco-friendly concretes. Since the demand for higher concrete strength are increasing rapidly, consumption of cement in the construction industry has increased about 600-700 kg/m^3 annually. The depletion of resources as basic raw materials may worsen the condition with the reduction of lime stone deposits. Thus in order to optimize the cement content that is needed most appropriately, which is required to investigate the efficiency of cement through detailed research.

- To produce ecological friendly, cost effective and cement efficient concrete product to overcome the environmental issue of increasing carbon dioxide (CO_2) emission in the atmosphere and depletion of major resources.

- Deterioration of reinforcing bars embedded in concrete through corrosion

- To align with the policy of sustainable development and the application of GREEN Technology in the Concrete Industry.

1.3 Objectives.

The principle objective of this research was to investigate series mixes that utilizes the optimum cement content and achieve high early strength. The targeted 28 days strength was 50-80 MPa. In order to achieve the main objectives, the following sub-objectives were designed:

- To determine the effects of aggregate grading on the efficiency of cement in concrete from 'Designed' and 'As-supplied' graded aggregate mixes. The high early compressive strength development is to be considered.

- To assess the durability performance of the series mixes through estimation of potential durability. The potential durability was estimated from the effects of aggregate grading and measured values of porosity, splitting tensile strength, chloride penetration and the Modulus of Elasticity (E-Modulus).

- To determine the relationship of cement consumption, energy efficiency in concrete production and economic efficiency of concrete materials. The amount of CO_2 emissions to measure how 'eco-green' the concrete materials with comparison with other research.

1.4 Scope of Works

For this research, the boundaries and the scope of works covers as stated below:

- The development of concrete material strength of 28 days and beyond. The high early strength development of day 3 and day 7 were also taken into consideration.

- The measurement of durability performance of concrete material to cater to ease concerns of researchers in the construction industry.

- The effects of aggregate grading without making OPC as the main contributor to achieve high strength in concrete materials.

- To reduce environmental impact by reducing OPC consumption and producing worksheets to ease designers in their calculations. The impact of the CO_2 emission was determined.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction and Background

P.C. Aitcin (2000) stated that the concrete is the most widely used construction material, the annual global production of concrete is about 5 billion cubic yards, (Cement Association of Canada, 2008). This is twice as much concrete is used in construction around the world than the total of all other building materials, including wood, steel, plastic and aluminum. As reported by USGS Minerals (2008), the concrete production is 17 billion ton/year. Cement is still an essential material in making concrete. The annual production of the 1.56 billion tons of ordinary Portland cement (OPC) worldwide results an equivalent amount of carbon dioxide CO_2 gas release into the air. In a simple term, making one ton of cement produces approximately 1 ton of CO_2 gas.

Concrete is easy to make, technologically simple and inexpensive in production that turned it an ideal construction material. Wherever concrete has many advantages, there are some weaknesses for its application. Concrete is generally specified by the requirements of 28-days compressive strength without taking into account the environmental conditions to which it is to be subjected throughout the service life. As a result, many concrete structures are prematurely failing, giving a bad image of concrete to the public. Besides that, concrete is also mistreated during placement and curing.

According to P.C. Aitcin (2006), concrete definitely presents technological advantages where it can be made from local inexpensive materials and can be cast in any shape. Concrete also have good compressive strength, it does not rot, not much affected by humidity, it does not burn and it is not attacked by insects. When it is well proportioned, adequately mixed, transported, placed and cured, it becomes a durable construction material under most environmental conditions.

Concrete is weak in tension, heavy, not volumetrically stable because it shrinks and creeps or sometimes swells. Moreover, concrete must be properly cured to reach its full potential as a structural material and its durability can be applied in aggressive environmental conditions usually in the marine conditions. (J.L. Baron and M.N. Oliver, 1999).

2.1.1. Building 'Green' and Preservations

As mentioned by T.L. Ir. Chen (2009), building green in the future is a necessity and not an option. This is because buildings consume 40% of our planet's materials and 30% of its energy. The construction of a building uses 2 to 3 million tons of raw materials a year where it is mostly concrete and generates 20% of the solid waste stream.

Construction materials provide engineers with real opportunities to contribute to a project's sustainability. In using the traditional criteria for material selection such as economy and appropriateness to project structural requirements, has already been an active participant in sustainable design. This can also be done by considering and exploiting the efficiency, availability and the impact a material has on the environment. Taking for example if the material is concrete, concrete consists mostly of cement paste binder and aggregates.

Concrete is also an essential structural material for constructing structures. Cement production contributes approximately 1.5% of United States (US) annual CO_2 emissions and is about 7% of worldwide annual emissions. Cement production produces approximately one pound of CO_2 for each pound of cement. Reducing the amount of cement used in concrete will reduce CO_2 emissions.

2.2. Problems and Issues with Concrete

2.2.1. Towards Sustainable Concrete.

Continuous advances in technology development in every industry are very critical and the construction industry required such. According to the Portland Home Builders Association of Metropolitan (2009), concrete is one of the most environmental friendly construction products. It offers durability, design flexibility and stability for the residential marketplace. It also exerts great environmental advantages through every stage of manufacturing and use where it is created to conserve the availability of raw materials worldwide.

Concrete is durable as it can sustain weather conditions and withstand aggressive environment threats. It is because of that concrete does not rust or burn. It is also less susceptible to moisture damage and can generally 'breathe' and dry if the concrete structure is not too close to adjacent structures.

By simply outlasting other materials, concrete conserves energy and resources. The criteria mentioned above are obviously seen in the creation of High Performance Concrete (HPC). To have quality construction, quality materials are highly in demand and to cater for all required criteria, HPC is definitely the product that every practicing engineers, contractors and manufacturers are looking for.

2.2.2 Cement Consumption in Concrete Production.

According to the Portland Cement Association (PCA) (2005), concrete consists mostly of cement paste binder and aggregates; cement production contributes approximately 1.5% of US annual CO_2 emissions and is about 7% of the worldwide annual emissions. Cement production produces approximately one pound of CO_2 for each pound of cement. Therefore reducing the amount of cement in concrete production greatly results in reduction of CO_2 emissions.

P. Lassere (2007) mentioned that cement is a basic ingredient for the construction industry and is made from the 80% limestone, 3% shell and 17% clay that are mined from quarries close to the plant. The raw material is crushed, and then heated at temperature in excess of 1000 °C in a rotating kiln to become clinker. The technology is a continuous process and is highly energy intensive. The cost of cement is derived as 29% energy, 27% raw materials, 32% labour and 12% depreciation which involved transfer of product to sites.

2.2.3. Cement Efficiency

M.L. Gambhir, (1997) reported that the compressive strength of the concrete increases with decreasing water to cementitious material ratio and with the increasing amount of SF. Thus, it is very important to understand the mechanism of the workability enhancement. The description is so as OPC and fine particles have a strong tendency to flocculate when mixed with water. The flocculation process leads to the formation of an open network of particles.

The network voids trap a part of the water, which is then unavailable for surface hydration of cement particles and for the fluidification of the mixture. These effects result in the stiffening or increase in apparent viscosity of the cementitious system. To achieve a homogeneous distribution of the water, and the optimal water cement contact, the cement particles must be properly deflocculated and kept in the state of high dispersion. Due to the dispersion effect, the fluidity in the cement mixture is increased.

The water reducing admixtures perform their function by deflocculating the lumps of the cement grain. In the normal stage, the surfaces of the cement grains contain negative and positive charges. As they bump into each other, they repel and attract. Superplasticizer on the other hand has very large molecules (colloidal size) which dissolve in water to give ions with a very high negative charge (anions).

These anions are absorbed into the surface of the cement particles in sufficient number to form a complete monolayer around them to become predominantly negative charged. Thus, they repel each other and flocs do not form. Because of that, the water trapped within the original flocs is released and it can contribute to mobility of the cement paste; hence, workability is improved. The representation of the superplasticizer molecule and its mode of absorption on cement grains are illustrated in Figure 2.1.

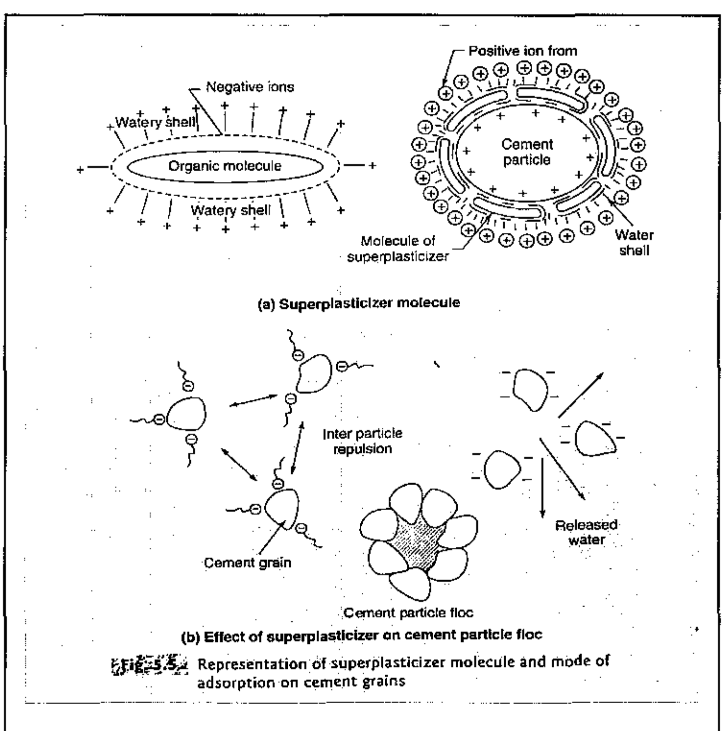


Figure 2.1: Representation of superplasticizer molecule and mode of adsorption on cement grains (M.L. Gambhir, 1997)

Thus, the amount of cement required within a mix is very important because it affects the strength of the concrete. The optimum amount is to be determined to ensure the quality of the concrete produced.

ACI (2005) estimated that for a 15% SF replacement of cement, there are approximately 2,000,000 particles of SF for each particle grain of OPC. A photomicrograph of the comparison of SF and OPC particles can be observed in Figure 2.2.

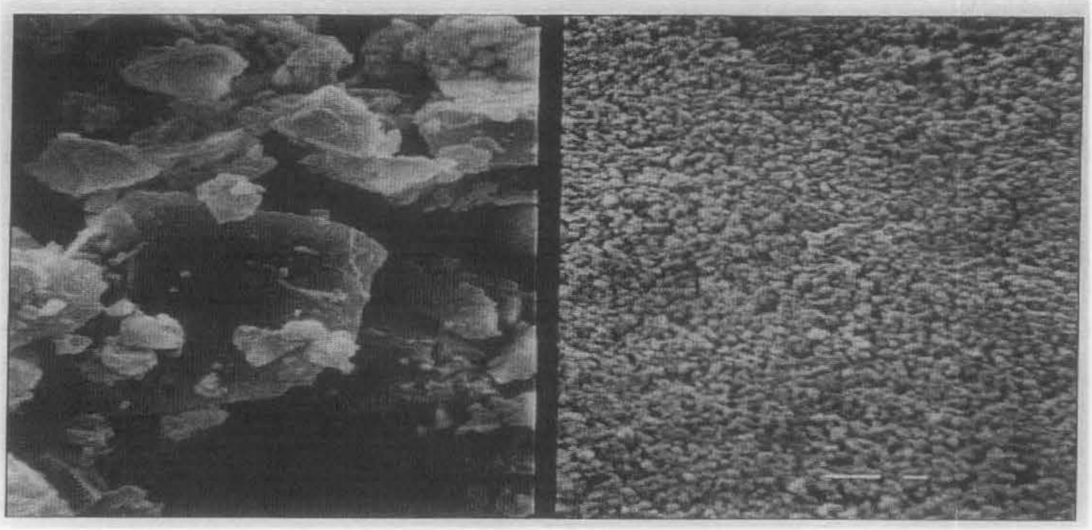


Figure 2.2: Comparison of OPC (left) and SF Particles (right) (ACI, 2005).

2.2.4. Environmental Impact of Concrete.

The amount of CO_2 embodied in a concrete depends primarily on the cement content of the mix designs. CO_2 produced during the manufacturing of cement is reabsorbed into the concrete during the product life-cycle. This particular process is called carbonation. Reabsorbtion of CO_2 also occurs over 100 year's life cycle and estimated absorption is to be in the range of 33% to 57%.

In terms of energy efficiency and energy consumption concerns, as defined by T.W. Bremner (2001), low energy consumption meant that the raw material to make both the cement and concrete is evenly distributed around the world and transportation is not the main consideration. The technology to make cement and concrete in many ways is similar to the technology used by the mining industry.

The advances in the mining industry have been adopted by the cement and concrete industry. In comparison with steel, aluminium, glass and plastic, the energy spent to create a concrete production facility in magnitude is less than what is required to create a comparable amount of competing material as can be seen from the cement kiln known to be a very energy efficient device. In addition, the energy to make concrete is mostly spent in making the cement.

The Environmental Council of Concrete Organizations (2006) mentioned that when evaluating the environmental aspects of building materials, concrete's overall impact is not harmful. Concrete is an ideal choice as a construction material as it actually helps to protect the natural resources and offers consumers benefits compared to other materials such as steel or timber. This can be observed in terms of resource efficiency, energy efficiency, waste minimization and prolonged structure lifespan.

However, the difference between cement and concrete have to be firstly understood. The two words which are concrete and cement are always being confused. Cement is actually one of the ingredients in concrete. It's in the form of fine greyish powder that when combined with water, binds sand and gravel or crushed stone into a rocklike mass known as concrete. Therefore even though cement is only 10%-15% by weight of the concrete's total mass, cement is the binding agent in concrete.

The severity of environmental impact is highlighted by K.P. Mehta (2001) as in the need for reducing the environmental impact of concrete is recognized in a recent report of the Strategic Development Council (2001). According to the report, 'Concrete technologists are faced with the challenge of leading future development in a way that protects the environmental quality while projecting concrete as a construction material of choice. Public concern will be responsibly addressed regarding climate change resulting from the increased concentration of global warming gasses.'

The Portland Cement Association, PCA (2005) reported that the cement production contributes approximately 1.5% of US annual CO2 emissions and is about 7% of worldwide annual emissions due to the demand of cement consumption during construction . Cement production produces approximately one pound of CO_2 for each pound of cement. Reducing the amount of cement used in concrete will reduce CO_2 emissions.

2.2.5. Natural Resources and Pre-Structural Deterioration

K.P. Mehta (2001) discovered that increasing the service life of structures is a long term and the fastest solution for preserving the Earth's natural resources. Thus, a new approach has been endorsed by the European Union known as the 'New Paradigm for Sustainable Development' suggests that minimization of materials use, maximization in product durability and reduction of maintenance cost will not only increase consumer's satisfaction and product value but also business profitability. When both manufacturers and consumers have achieved interest in improving the resource productivity, the world's ecosystem will be protected.

Ordinary concrete contains 12% cement and 80% aggregate by mass. Thus the annual global consumption of sand, gravel, and crushed rocks is at the rate of 10 to 11 billion tons. The mining, processing and transport operation involving large quantities affects the ecology of forested areas and riverbeds. Besides the three primary components; cement, aggregates and water, various chemical and mineral admixtures are also added into concrete mixtures not forgetting batching, mixing, transport, placement, consolidation and finishing of concrete.

Lack of durable materials causes pre-structural deterioration. Concrete structures are designed for a service life of 50 years, but experience shows that in urban and coastal environments many structures begin to deteriorate in 20 to 30 years or even less. This matter is not as wanted by many parties and is usually categorized as bad construction planning.

Considering funding constraints in high repair and maintenance works, it is suggested that in future structures are to be designed and built for a minimum service life of 100-120 years. The trend towards designing infrastructure based on life-cycle cost will not only maximize the return of available capital but also available natural resources.

S. Aiken and C.H. Leigh (1992); J.R. Vincent and R.M. Ali (1997) and World Bank (1987) mentioned that Malaysia is filled with natural resources especially minerals such as limestone and rocky mountains. Malaysia's heavy reliance on its natural resources has been a salient feature from colonial days up until the 1970s.

2.2.6. Silica Fume Application – World and Malaysia.

In Malaysia the application of Silica Fume (SF) in the construction of structures is still in the preliminary stage. A step towards real understanding of SF and introductory to its application in the construction industry is greatly required. A.M. Neville (1995) and V.M. Malhotra and K.P. Mehta (1996) reported that since the development of Portland Cement by Joseph Aspdin in 1824, there have been some developments throughout the 20th century from the use of pozzolanic by-products such as SF in order to cut down the fuel cost and CO_2 emissions in the manufacturing process for example in cement and concrete productions.

At the same time turning waste to by-products, reusing of materials help reduce waste from industries, moving towards sustainable construction. Although its advantages are recognized more as compared to before, only a small percentage of the current supply of SF is being used as a mineral admixture in the cement and concrete industries.

M. Gary and J. Scanlon (2001) also mentioned that in the refractories world thirty five years ago, no one was working with SF and few knew what it was. Within a few years, it was being use as an additive in bricks. When the chemical is applied into the High Alumina Brick, mullite was formed in the matrix of the brick on firing, giving the brick good volume stability, strength and chemical resistance. At that time, it was only logical that silica fume would be used in brick and in no other construction materials. Silica fume is the pioneer in this transformation where SF has gone beyond having the brick-like properties too actually out performing brick in many applications.

2.2.7. Energy Consumption in Concrete

The cement industry is said to be an energy-intensive industry together with steel, paper and petrochemical industries. The percentage of energy cost in Portland cement production cost is 20% to 30%. If the energy cost is reduced, the manufacturing cost is lowered. Thus this results in increasing the company's profits. UNIDO (2001)

Energy is crucial in all aspects of development from empowering manufacturing and modernization. Although new alternative, renewable, cleaner and more efficient technologies are being developed and implemented every year, the main strain by the rise in energy demand and global consumption outweigh the benefits brought by these improvements. The challenge lies in finding a way to reconcile the necessity and demand for energy supply with its impact on the natural energy resources in order to ensure a sustainable path for development (A.R. Mohamed and K.T. Lee, 2004).

As Malaysia's economy sector is developing, a recovery of energy in energy demand is very critical. According to J. Thaddeus (2002), the energy generating capacity within the last three years (increases according to energy demand) has increased almost 20% from 13000 MW to 15500 MW in the year 2003. The energy generating capacity is estimated to increase to 22000 MW by the year 2010. In order to meet the increasing demand, energy supply infrastructures have to be developed and be capital intensive. Consequently, this will impose tremendous pressure on natural resources.

At the same time, with the current pattern growth, resource used and environmental degradation cannot be ignored if looking to the future. Since the large demand has been placed on building material industry especially in the last decade, owing to the increasing population, which causes a chronic shortage of building materials the architects and civil engineers have been challenged to discover useful building and construction materials.

As mentioned by M.S.E. Sherif (2009), the increase in the popularity of using environmental friendly, low cost and lightweight construction materials in building industry has brought about the need to investigate how this can be achieved by benefiting to the environment as well as maintaining the material requirements affirmed in the standards. The standards can be obtained in Appendix E.

Therefore, it is logical to think that, in the immediate future, urban growth and its infrastructures will continue to produce maximum impact on the natural environment through the use of materials and the consumption of raw materials and energy. The number of construction works shall progressively increase however; these shall be undertaken by attempting to achieve the paradigm of sustainability, demanding an increasing durability of what is being built in order to minimize environmental impact. Thus as reported by B. Cazacliu and N. Roquet, 2009, to enhance production of HPC with low power consumption, new kinetic models using rheology and

2.2.8. Durability, Lifespan and Cost Consideration of Concrete

Touching the issue of durability and lifespan, concrete production continues to be a much debated issue in Malaysia. Often the Ready Mixed Industry is blamed for not being up to mark but the problem is much more complex than just poor performance at the batching plant (G.N. Kribanandan, 2000).

Today concrete is a complex material consisting not only of cement, aggregates and water but also admixtures and cement replacement materials. Concrete problems can arise from a few causes as stated below:

1. Inadequate specification
2. Batching Problems
3. Site Logistics and Long transport times
4. Poor placement
5. Lack of attention to finishing and curing

An inadequately prepared specification is the first problem. Problem structures were investigated where on occasion the specifications refer to CP110 a code which has not been in use for over two decades. In other cases the cutting and sticking of specifications from one project to another. This causes irrelevant code practices in projects especially when it comes to concrete testing before application in construction.

Problems at the batching plants do exist but increasingly the larger companies are much well organised, with internal training and many are ISO 9000 accredited. Site logistics and long transport times can be overcome by good planning and concrete designed for long setting times. Construction problems such as poor placement, finishing and curing are a function of poor training and lack of supervision. The issue of training and skills development in the construction industry clearly needs urgent attention.

During the design process it is normal to select a concrete strength requirement on the basis of 28 day strength of a cube (or in some countries a cylinder) tested in compression. The justification for this is the wealth of information that relates such an arbitrary test to observed structural performance. Even at this stage it is appreciated that the compressive strength as measured is only valid for the cube and in absolute terms shows only the potential for the concrete when used elsewhere in a structure itself. So we have a convenient assessment with which designers can work which is on a 28 day compressive strength requirement.

At this stage it should be remembered that in arriving at the quality (strength) of concrete, designers will have already incorporated some safeguards for uncertainty into the design process. Partial safety factors are used to increase material strength requirements to allow for some variability in the materials in a structure and in test specimens.

In selecting concrete type and mix, the need to provide concrete to a reliable standard involves an appreciation of the variability of the constituents that make up a concrete mix as well as its inherent non-uniformity. A statistical approach is taken to allow for variability. In this way the minimum strength requirement is increased so that a characteristic strength is selected and used as a target that within the scale of variability will mean that only some 5% of the test results will fall below the minimum specified level. While this provides a working platform for concrete production it should also mean that the majority of concrete used will be above or well above the limit.

To deal with concrete strength which is very much demanded in urban and offshore constructions, durability and service life issues are seldom considered except during remedial works. Concrete if it is understrength and has low cover provide the ideal conditions for the ingress of the environment to the level of reinforcement .

Possible initiation of corrosion mechanisms. If the buildings are away from the marine environment, the primary corrosion mechanism might be carbonation damage. A low strength cover concrete could reduce time to penetration considerably. This proves that quality 'Green' concrete mixes are very much required in the construction of urban and offshore structures.

2.3 Important Engineering Properties.

2.3.1 Ideal Concrete Mix Designs

Concrete mix design is the process of selecting suitable ingredients of concrete and determining their relative quantities with the objective of producing the most economical concrete while retaining the specified minimum properties such as strength, durability, and consistency (G. Akhras and H.C. Foo, 1994).

The easiest way to do mix design is to use proportions established for similar concrete using the same materials. Previous experience with concrete material is also of immense advantage in concrete mixture proportioning and adjustment. Where these are lacking the only possible option is to proportion the ingredient by a trial and error process. Several methods and codes are available to serve as guide for mix design of normal concrete (ACI Committee, 1991; R.E. Teychenne and W.A. Erntroy, 1988) and high performance concrete (P.C. Aitcin, 1998; ACI Comittee, 1995; G. de-Larrard, 1990 and K.P. Mehta and P.C. Aitcin, 1990). However, these are just guides to arrive at first trial mix.

Optimum mix proportions are obtained through testing of trial mixes and making adjustment accordingly (M. Kett, 2000). This is because these codes were developed based on experience with materials in certain parts of the world and may not be applicable to mix design in other parts of the world. Also, these codes do not address all issues regarding concrete mix design such as admixtures, transportation, and temperature effect (G. Akhras and H.C. Foo, 1993).

Concrete with several properties may be desired such as high workability, medium workability, high strength, lightweight, insulation etc. These challenges cannot be met by designing mix proportions based on existing codes and methods of concrete mix design. Concrete mix design and adjustment is complex and the correct way to perform this can be achieved with expert's advice and experience (M.F.M. Zain *et.al,* 2005).

2.3.2 Strength Consideration of Concrete in Construction Industry

The strength is one of the most important engineering properties of concrete. It reflects its mechanical quality and provides an indication of many other properties. The strength and durability of concrete are influenced by the use of cementing supplementary materials such as silica fume, rice husk ash, fly ash and etc. T. Brunauer and M. Copeland (1964) mentioned that the general factor affecting strength of concrete is water-cement ratio (w/c). The properties of concrete are largely governed by the cementatious matrix.

In particular, the strength of concrete is essentially dictated by the capillary porosity, which is a function of the w/c and degree of hydration of the cement particles. High w/c concrete contains a larger pore space than a lower one. This effect influences the strength of the hardened cement paste, which is the dominant factor in the strength of concrete. In other words, the strength of concrete resides in the solid part of the paste.

The knowledge of the 28 days compressive strength of a concrete is fundamental to be used in calculations that will allow the construction of a structure so that it is safe maintaining its mechanical strength during the whole life of the structure. The overwhelming importance of the compressive strength of concrete has been a constant preoccupation and links with the durability of the concrete. (P.C. Aitcin, 2000).

2.3.3 Mechanical Properties and Enhanced Durability of Concrete.

If discussed in terms of mechanical properties, K.C. Hover (1998) discovered that low water cement ratio (w/c) is responsible for improved mechanical properties and for enhanced durability. Water reducing admixtures can be used for the purpose of increasing the durability of e concrete, primarily by means of decreasing porosity, permeability and improving the mechanical properties. Such improvements do not only slows the rate of water but also oxygen, carbon dioxide and dissolved solids.

It will also provide increased resistance to stresses generated by external or internal loads. External loads include typical service loads, impact or abrasion while internal loads includes internal expansion of freezing water, alkali-silica gel, swelling aggregates, ettringite crystals or thermal stresses. If concrete is exposed to extreme temperatures (freezing for cold countries and extreme heat in hot countries), admixtures can be added to the concrete for specific resistance, another aspect of durability.

Durability of concrete structures is always a concern in aggressive environments. Factors to be considered in dealing with the durability of concrete includes concrete constituent materials, construction processes, physical properties of the concrete, type of loading and the nature of the environment to which the concrete structure is exposed.

The major durability problem such as the corrosion of steel reinforcement and cracking due to the reaction between alkalis released during the hydration of cement and certain types of aggregates, are caused by fluids penetrating the pore system of the concrete. Therefore as mentioned by A.S. El Dieb (1995), the porosity of concrete is critical to its durability in many service environments. Environmental conditions effects greatly the durability of concrete. One of the most aggressive environmental agents is chloride (found in soil, groundwater and seawater).

2.4 Concrete Properties and Material Performance

In this research, the properties of concrete were measured in the fresh and hardened conditions, Properties in fresh condition are very important as it controls the performance of concrete in the hardened condition.

2.4.1 Fresh Concrete Condition

2.4.1.1 Slump

Slump is measurement of the workability or fluidity of concrete. A stiffer mixture will have a low slump value. The higher slump values shows that the particular concrete mix has high workability. The decrease in the height of the slumped concrete is term as *slump* and it is measured to the nearest 3mm - 5mm. The decrease is measured to the highest point according BS1881: Part 102 (1983). There are three type of slumps which includes true, shear and collapse slump. (A.M. Neville, 1995)

Superplasticizer is commonly used to disperse cement particles. When added into cement paste, the value of the paste decreases close to zero. Then the paste and concrete will obtain good flowability without the segregation of raw materials. Naphthalene sulfonate Superplasticizer is often used to improve the rheology of fresh concrete.

When naphthalene sulfonate plasticizer is adsorbed to the surface of cement particles, it changes the sign of the zeta potential of the particle surface to the negative charge and increases the absolute value. Cement particles having the same sign of zeta potential cannot approach each other closely due to the electrostatic repulsion (P. Ternkhajornkit and T. Nawa, 2004).

2.4.2 Hardened Concrete Condition

2.4.2.1 X-ray Fluorescence Spectrometry (XRF)

XRF technology provides one of the simplest, accurate and economic analytic methods for the determination of the chemical composition of many types of materials. The strengths of this analytical method include easy sample preparation and are suitable for solid, liquid and powdered samples; analysis of non-conducting materials (notably oxides, glasses, ceramics and plastics) and exceptional precision, particularly for high concentration levels.

The XRF works when a primary x-ray excitation source from an x-ray tube or a radioactive source strikes a sample, the x-ray can either be absorbed by the atom or scattered through the material. The process which an x-ray is absorbed by the atom by transferring all of its energy to an innermost electron is known as photoelectric effect.

During this process, if the primary x-ray had sufficient energy, electrons are ejected from the inner shells and in the process give off a characteristic x-ray whose energy is the difference between the two binding energies of the corresponding shells. Since each element has a unique set of energy levels, each element produces x-rays at a unique set of energies, allowing one to non-destructively measure the elemental composition of a sample. (Amptek Inc., 2002)

Thermo Fisher Scientific (2007) stated that the control and Research and Development (R&D) tasks can be undertaken and precision inside ±0.1% relative is routinely achieved whilst limits of detections are often at parts per million (ppm) or sub ppm levels. The XRF technique is also widely acceptable and used in the metals industry alongside Optical Emission (OE) spectrometers. This combination brings the optimum configuration for rapid and accurate analysis of both metals and the oxides associated with metal production such as ores and slag.

For sample preparation, in order to keep the geometry of the tube-sample –detector assembly constant, the sample is normally prepared as a flat disc, typically of diameter 20-50 mm. This is located at a standardized, small distance from the tube window. Since the X-Ray intensity follows an inverse square law, the tolerances for this placement and for the flatness of the surface must be very tight in order to maintain a reputable X-ray flux.

There are several ways to obtain sample discs depending on the materials that need to be tested; metals may be machined to shape, minerals can be finely ground and pressed into tablet ad glasses may be cast into required shape.

The purpose for obtaining a flat and representative sample surface is that the secondary X-rays from lighter elements often only emit from the top few micrometers of the sample. In order to further reduce the surface of the irregularities, the sample is usually spun at 5-20 rpm. It is important to ensure that the sample is sufficiently thick for absorption. For higher-Z materials, a few millimeters thickness is adequate, but for a light-element matrix such as coal, a thickness of 30-40mm is required.

2.4.2.2 X-Ray Diffraction Spectrometry (XRD)

According to the Limnological Research Centre Core Facility (2004), a routine XRD mineralogy profile can provide qualitative and semi-quantitative records of shifts in the source of sedimentary components to a lake sequence. XRD mainly displays information on autocthonous and authigenic minerals. But can give some indication of the abundance of amourphous silica phases. Set up with routine data collection, XRD is a rapid, accurate technique which can process 40 samples per-day using an automated sampler charger.

Each mineral is defined by a crystal lattice with characteristic diffraction properties resolved by x-rays. The Angstrom d-spacing of certain crystallographic lattice directions show up as relative peak (area) heights on the diffractogram (usually in mm) in a fixed relationship to the 2θ (two-theta) angle of the scintillator counter as defined by Bragg's Law of the diffraction. Using calibrated peak area intensities of the major peak, the proportion of mineral species in a profile can be given with about ±5% at least for minerals which constitutes more than 5% of the bulk sample.

Figure 2.3 shows that based on Bragg's Law, $n\lambda = 2d\sin\theta$, by controlling the wavelength with vary and continuously measure the incident angle, it will leave only the lattice plane spacing as variable. So whenever a constructive interference is observed, at a point a fundamental spacing parameter for the mineral of interest can be calculated (G. Arehart, 1999).

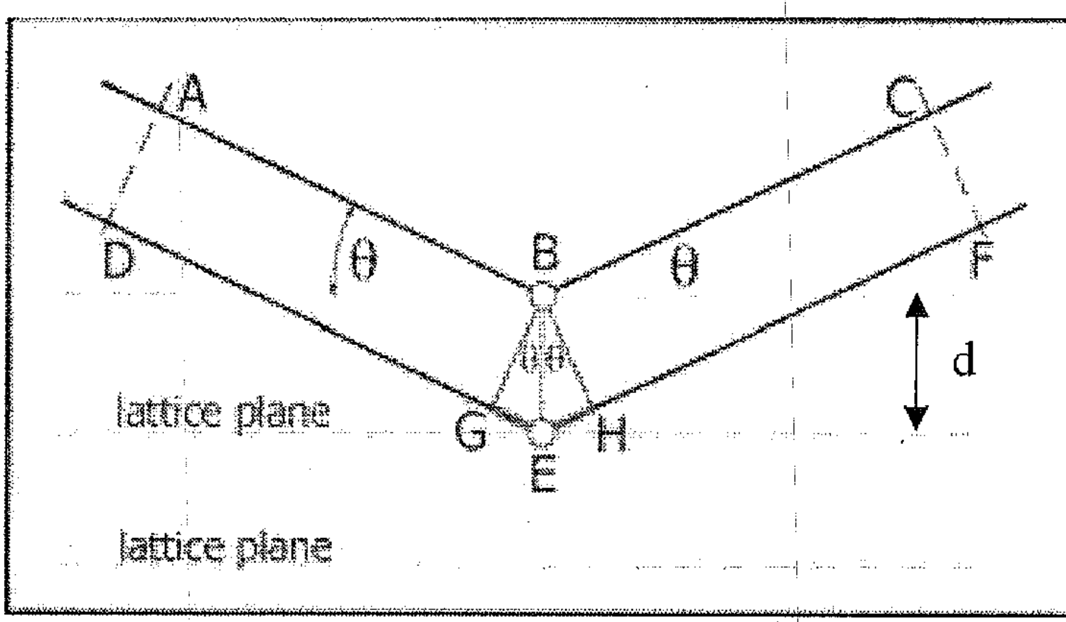


Figure 2.3: Geometry of X-Ray Reflection (G. Arehart, 1999)

2.4.2.3 Compressive Strength

The National Ready Mix Concrete Association, NRMCA (2000) reported that the compressive strength of concrete is a primary physical property and frequently used in design calculations for bridges, buildings and other structures. Conventional concretes have a compressive strength between 20 MPa to 35 MPa. For high strength concretes by definition has a compressive strength of at least 70 MPa. Compressive strengths up to 140 MPa have been used in special bridges and high-rise building applications.

Concrete mixes can be designed to provide a wide range of mechanical and durability properties to meet the required codes and standards of a structure. The compressive strength is measured by breaking concrete cube specimens in the universal testing machine for compression. The compressive strength is calculated from the failure load divided by the cross-sectional area resisting the load and reported in the units of pound-force per square inch (psi) in US customary units or Megapascal (MPa) in SI units.

The compressive strength test results are mainly used to determine if the concrete mix as delivered meets the requirements of the specific strength f'_{cr} in the job specification. A test result is the average of at least two or usually three standard cured strength specimens made from the same concrete sample and tested at the same age. In most cases, strength requirements for concrete are at the age of 28 days.

2.4.2.4 Porosity

Porosity is related to the original packing of the cement, mineral admixtures and the aggregate particles; the water-to-solids ratio; the rheology, which is related to the degree of dispersion of the solids originally present; and the conditions of curing.

The weight of the moisture and relative humidity in concrete with regards to the durability is highlighted. According to K.P. Mehta *et.al* (1993), permeability of concrete is influenced by two main factors: porosity and interconnectivity of pores in the cement paste and micro-cracks in the concrete, especially at the paste aggregate interface.

J. Berissi *et.al* (1986) proved that porosity and interconnectivity are controlled for most parts by the water cement (w/c) ratio, degree of hydration and the degree of compaction. On the other hand, density and location of interfacial micro-cracks are determined by the level of applied stress, external or internal which is experienced by the concrete.

Internal stresses in concrete occur as a result of shrinkage, thermal gradients, abrupt changes in the hydro-thermal environment and factors causing volumetric instability. In high performance concrete, it has been shown that the macroscopic property is related to the porosity. It is from this idea porosity is tested in this research.

2.4.2.5 Splitting Tensile Strength

Splitting tensile strength is obtained from split-cylinder test conducted on cylinder concrete samples. Tensile strength can also be obtained from an unreinforced concrete beam or slab to resist failure in bending. The general test includes the measurement done by loading 150 mm x 150 mm concrete beams with a span length at least three times of the depth. The flexural strength is expressed as *Modulus of Rupture* (MR) in psi or MPa. Standard tests methods are used such as ASTM C78 (third point load) or ASTM C293 (center point loading) (The National Ready Mix Concrete Association, NRMCA, 2000).

Flexural MR is about 10%-20% of compressive strength depending on the type, size and volume of aggregates used. However the best correlations for specific materials are obtained by laboratory tests for some specific materials and mix design. The MR which is determined by three points loading is lower 15% than the MR determined by the center point loading.

As mentioned by Instron (2007), flexure testing is often done on relatively flexible materials such as polymers, wood and composites. There are two test types; 3 point bending and 4 point bending. In 3 point bending test, the area of uniform stress is quite small and concentrated under the center loading point. As in a 4 point, the area of uniform stress exists between the inner span loading points (typically half the outer span length).

2.4.2.6 Modulus of Elasticity (Flexural Tensile Strength)

As described in the ASTM C469 (1986), modulus of elasticity is the stress to strain ratio value of hardened concrete at whatever age and curing condition that may be designated. The standard also states that the modulus of elasticity is applicable with the customary working stress range of 0%-40% of the ultimate concrete strength. The modulus value is usually used in sizing reinforced and non-reinforced structural members, establishing the quantity of reinforcement, computing stress for observed strain and in the design of pre-stressed concrete members.

As reported by S. Bhanja and B. Sengupta, (2005), flexural tensile strength also known as the modulus of elasticity, plays a vital role in concrete making. In concrete, cracks can propagate very easily in tension and the cracking of concrete may cause serviceability and durability problems. The use of Silica Fume (SF) can improve the mechanical properties of concrete by replacement in different levels and percentages as well as strength improvement in the transition zone of cement paste.

Modulus of elasticity of concrete is expressed in terms of compressive strength. The mechanical properties of concrete are highly dependent on the properties and proportions of binders and aggregates. Modulus of elasticity is also known as the tensile strength of concrete and is a key factor to estimate the deformation of buildings and members. It is also a fundamental factor for determining the modular ratio, n which is used for the design of section members subjected to flexure (T. Fuminori and M. Noguchi, 1990).

L. Nawa and G. Horita (2004) described that the standard used for determining the Static Modulus of Elasticity of concrete in compression is the ASTM C 469. The standard describes modulus of elasticity as the stress to the corresponding strain ratio value for hardened concrete at whatever age and curing condition.

2.4.3. Durability of Concrete in Marine Condition

Concrete exposed to marine condition according to B.C. Gerwick (1986), may deteriorate due to effects of chemical action of the seawater constituents on cement hydration products, alkali aggregate expansion, crystallization pressure of salts within concrete if one face of the structure is subject to wetting and others to drying conditions, frost action in cold climates, corrosion embedded steel in reinforced or pre-stressed members and physical erosion due to wave action and floating objects. Attack on concrete by any of these causes will increase the permeability and porosity of the concrete.

As summarized by P.F. McGrath (1996) the causes of concrete deterioration are classified into two categories which are the physical and chemical causes as shown in Figure 2.4 and Figure 2.5.

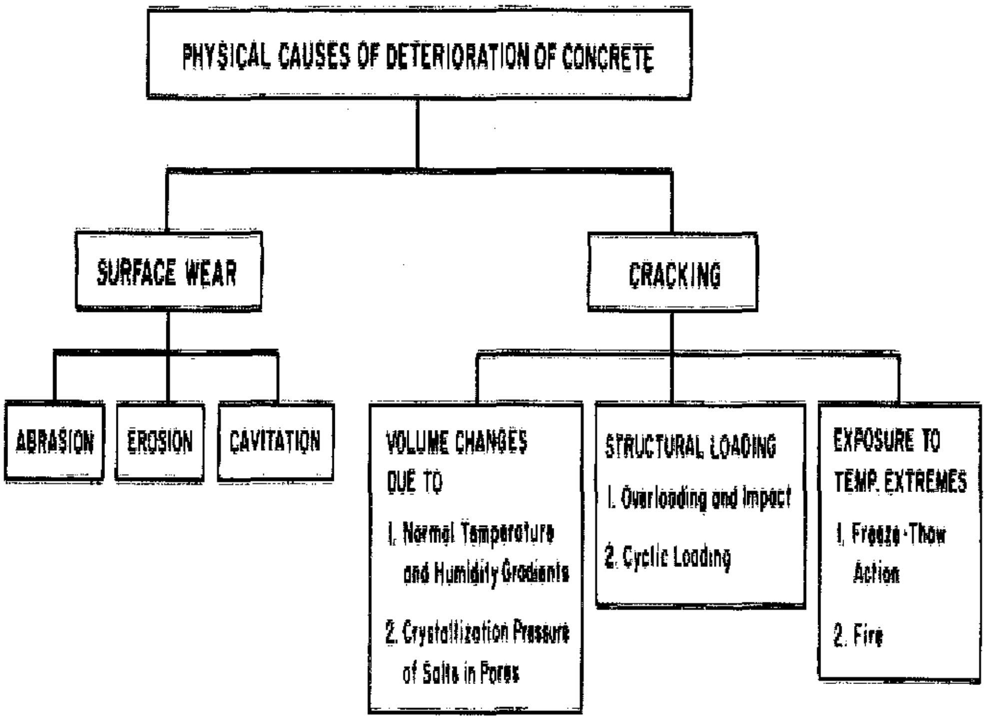


Figure 2.4: Physical Causes of Deterioration of Concrete (P.F. McGraft, 1996)

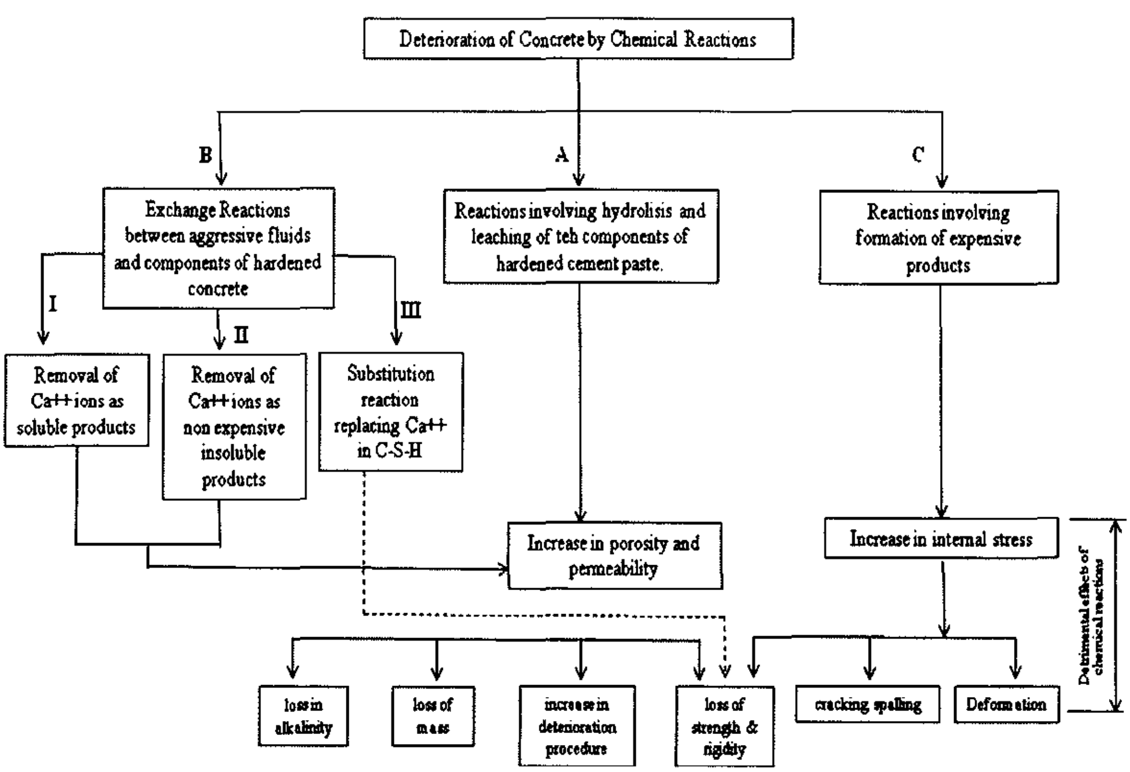


Figure 2.5: Corrosion of Concrete by Chemical Reactions (P.F. McGraft, 1996)

Expansion and micro cracking due to physical effects of pressure from salt crystallization in a permeable concrete will increase the permeability further and pave the way for deleterious chemical interactions between seawater and cement.

In terms of corrosion of reinforcing steel, G.C. Hoff (1986) and T. Mays *et.al* (1992) states that, when a concrete structure is exposed in deicing salts, salt splashes, salt sprays or seawater, chloride ions, those constituents will slowly penetrate into the concrete, mostly through pores in the hydrated cement paste. The chloride ions will eventually reach the steel and then accumulates to beyond a certain concentration level, the protective film is destroyed. This causes the steel to corrode when oxygen and moisture are present in the steel-concrete interface.

Once corrosion sets in on the reinforcing steel bars, it proceeds in electrochemical cells formed on the surface of the metal and the electrolyte or solution surrounding the metal. Each cell consists of a pair of electrodes (the anode and its counterpoint, the cathode) on the surface of the metal, a return circuit, and an electrolyte. Basically, on a relatively anodic spot on the metal, the metal undergoes oxidation (ionization), which is accompanied by production of electrons, and subsequent dissolution.

These electrons move through a return circuit, which is a path in the metal itself to reach a relatively cathodic spot on the metal, where these electrons are consumed through reactions involving substances found in the electrolyte. In a reinforced concrete structural element such as beams, columns or slabs, the anode and the cathode are located on the steel bars, which also serve as the return circuits, with the surrounding concrete acting as the electrolyte. This can be observed in Figure 2.6.

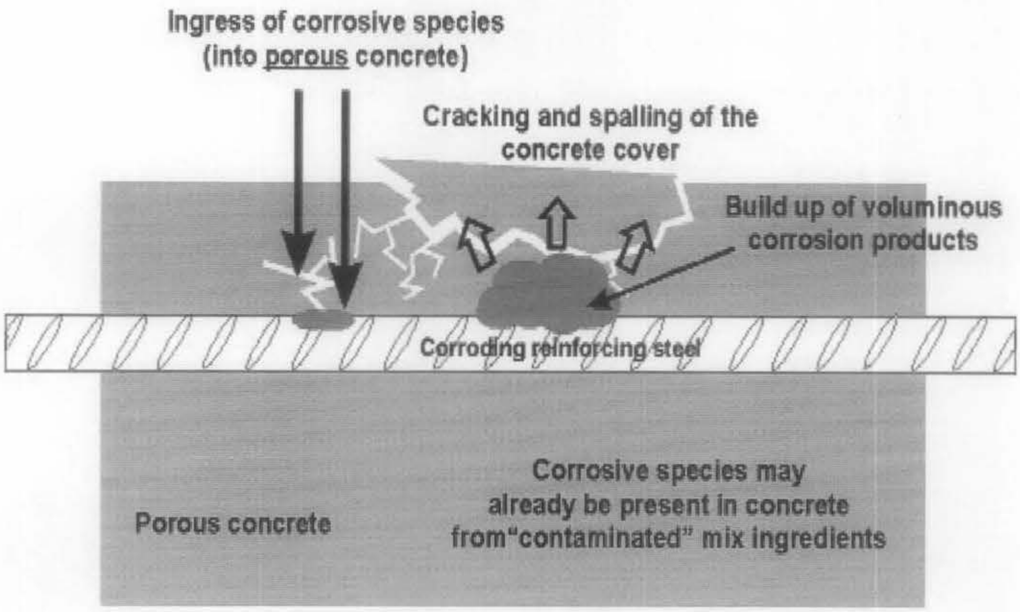


Figure 2.6: Corrosion of Reinforcing Steel (T. Mays *et.al*, 1992)

2.5. Modernization of Concrete

2.5.1. Modern Concrete Technology

As mentioned in P.C. Aitcin (2000), modern concrete is also known as the concrete of tomorrow. Modern concrete will be greener where it will have a low water cement (w/c) ratio; it will also be more durable and have various characteristics that will be quite different from one another for different applications. Concrete can now be designed as demanded. Concrete and cement producers have to realize that more profit can be made by selling small amounts of concrete 'customized' rather than a cheap commodity product. The cost of 1 MPa or 1 year of life cycle is more important if compared to the cost of 1 m^3 of concrete.

Concrete producers in future will have to differentiate the types of concrete offered by the cement and admixture producers. This is to provide contractors concrete that is more high tech and economical. This will not only be in terms of cost of 1 m^3 but in terms of performance. An example of the modern concrete technology is the High Performance Concrete (concrete with added admixtures).

2.5.2. Innovation in Concrete Technology

According to M. Ali (1997), in concrete construction, much of the technological changes were in the first half of the 20^{th} century. Advances in formwork, mixing of concrete, techniques for pumping and types of admixtures to improve quality have all contributed to the ease of working with concrete in construction which also includes construction under aggressive conditions.

When transport began at 1913, it was executed using open trucks. Since segregation occurred on the way to the site, remixing was required. Actual means of transporting the quantities needed for enormous job as construction project entails by a transit-mix vehicle was not available until after 1920. In 1947, the first "hydraulically driven truck mixers" were introduced in the scene.

Delivery of concrete and material placements in large quantities has been an issue in urban and marine constructions. Technology remained primitive and stagnant in this area until 1960s when hydraulically powered and controlled pumps were first developed and mounted on a truck for mobile services. From here techniques improved continually until now when pumping of concrete is also considered in small construction projects.

Great thought must be considered to the properties of concrete during construction in effort to reduce consumption of energy through the usage of high-tech facilities such as pumps that requires high energy capacity.

2.5.3. Improvements in Concrete Technology

Along with advances in the ways that concrete is brought to the site, the types of formwork in which it is cured, and how it is placed at high levels, its mechanical and chemical properties have made great advances in the past century.

The most significant improvement is the application of High Performance Concrete (HPC) in urban and marine constructions. HPC truly began in 1927 when engineers were building a tunnel through the Rocky Mountains near Denver. The construction needed a quick way of supporting the loads on the tunnel. At that time, HPC, is under research stage and was not ready to enter the market. The engineer prevailed upon scientists to allow its use. Eventually, the tunnel was built using HPC. The builders were very interested in HPC as it has the ability to reach an adequate maturity in 24 hours rather than 7 days for regular concrete. HPC is also very different from conventional reinforced concrete and contains admixtures.

HPC is also an ideal choice among contractors. It encompasses more than just high-early performance. It is a mixture whose properties include increased strength and better performances in the areas of durability, ductility, density, mixture stability and chemical resistance. It also changes depending on the type of admixture combined with cement, aggregates and water for the final product. Building industry professionals are also very interested in increasing productivity by decreasing the amount of time for concrete to reach its strength and amount of material required to carry the loads of a structure as well as having improved stability and toughness.

HPC is very flexible with applications to many classifications of construction. It is well known that time, money and labour costs together are a matter of great concern in the building industry. With its low water cement (W/C) ratio, strength of 20 to 40

MPa can be developed within 24 hours of placing. This performance speeds the time for project completion and may reduce cost with the reduction of waiting time and more reuse periods for formwork. Higher strengths that can be achieved by HPC also add a few other beneficial effects to the structure. These features of HPC make it appropriate for applications to building constructions in urban and marine environment (M. Ali, 1997).

According to J. Hu and L. Larrard (1996), HPC has been widely used in the last decade. With superplasticizer added into concrete mixes, reduction of water happens in concrete mixes resulting in better compactness. The SF used in certain cases increases even more the concrete compactness by filling of some intergrain voids. Hence the HPC presents numerous advantages.

From G.N. Edward *et.al.* (2003), in order to cater to the world development and the increasing urbanization, HPC with high strength is highly needed so to sustain the capacity of a structure that is subjected to carry. This is so by reducing the size of the structural elements and maintaining the required strength of the concrete material. This saves cost for all parties and promotes technology development to the Concrete Industry.

2.6 Introduction to High Performance Concrete (HPC).

2.6.1. Background

'All high performance concrete is high strength concretes but not all high strength concretes are high performance concretes' (H.G. Russell, 1999)

HPC is not one product but a technology which includes a range of materials with special properties beyond conventional concrete and the routine construction methods. According to T.C. Holland (1997), ACI President, HPC is an 'umbrella term for many exacting specifications for concrete construction'.

From S.C. McCraven (2002), HPC is relatively a new type of technology. HPC began in France in 1980 followed by Canada in 1990. In 1989, under the direction of Paul Zia from North Carolina University, a major effort in HPC technology began in the United States with the initiation of the Strategic Highway Research Program (SHRP). SHRP defined HPC in terms of strength, low water/cement (W/C) ratio and durability towards aggressive environments. These early efforts were in response to the critical deterioration rates of the nation's roads and bridges.

2.6.2. Global Development

M.L. Gambhir (1997) states that the Compressive Strength of HPC is much higher than those of the normal concrete of the same consistency. Strength of the normal concrete is achieved by concrete with reduced cement content. The use of superplasticizers generally improves the strength of HPC. The strength of concrete normally depends on a number of factors including the properties and proportions of the constituent materials, degree of hydration, rate of loading, method of testing and specimen geometry.

The properties of the constituent materials which affect the strength are: the quality of fine and coarse aggregates (well graded and have good distribution), the cement paste and the paste-aggregate bond properties of the interfacial transition zone. These, in turn, depend on the macro- and micro-scopic structural features including total porosity, pore size and shape, pore distribution and morphology of the hydration products as well as the bond between individual components.

As reported by H.G. Russell (1999), high strength is also known as high performance concrete and has been used in the columns in high rise buildings. The economic advantages of using HPC in the columns of high-rise buildings have been known for many years. The three major components contributing to the cost of a column are concrete, steel reinforcement and formwork. By utilizing HPC, the column size is reduced. Indirectly less concrete and less formwork are needed. At the same time, the amount of vertical reinforcement can be reduced to the minimum amount as long it is within the range specified by the code.

As a result, the least expensive column is achieved with the smallest size column, the least amount of reinforcement and the highest readily available concrete strength. Now, HPC has it all and is not only used widely in building constructions or bridges but also in carparks and marine structures (foundations and platforms).

2.6.3. Working with Silica-Fume Concrete

Aberdeen Group (1987) reported that, SF produces concrete that is stronger and more durable than conventional concrete. Field strengths of 80MPa have been achieved with this highly reactive pozzolan. Also, rebar corrosion is reduced because the reaction products of the extremely fine silica fume particles fills in the internal pores. This slows carbonation and helps keep chlorides out of the concrete. Because of these benefits, many engineers are now specifying silica-fume concrete for high-strength structural applications and abrasion-resistant surfaces.

This is modern concrete technology. Construction workers must be carefully trained to get the best results in handling concrete with SF. There is little or no bleeding in flatwork, so finishers must adjust the timing of finishing operations and structures exposed to de-icing agents or salt water. The addition of SF isn't a substitute for good concreting practices, however, it is for best results. Concrete suppliers must pay close attention to several production details. Contractors must also need to know how placing, finishing, and curing procedures differ from those used for conventional concrete.

SF in concrete acts much like conventional concrete during transport, placement, and consolidation. However, depending on the amount of SF, the fresh concrete can be more cohesive and less prone to segregation than conventional concrete. For overall ease of placing and finishing, the slump is made as high as is practical. Concrete with SF can be transported in any equipment used to transport conventional concrete. After discharge, the equipment should be cleaned the same way as for conventional concrete.

Concrete with SF can be placed successfully using any placement device such as a bucket, pump, or tremie. During placing, water should not be added into the concrete to improve workability. Just as with conventional concrete, too much water reduces strength and durability. If a higher slump is needed, controlled amounts of a water-reducing admixture at the batch plant or at the jobsite is added. Consolidation by vibration is needed for silica-fume concrete even when a high-slump mixture is used. Concrete with a slump of 8 to 10 inches can be deceptive because it flows so well that workers may think vibration isn't needed. However, the increased cohesiveness caused by SF entraps air which must be removed by vibration, regardless of the slump.

The biggest difference between conventional concrete and concrete with SF shows up during finishing. Adding up to 5 percent silica fume by weight of cement makes little difference, but adding higher amounts of silica fume reduces bleeding and may eliminate it. This makes SF concrete more rapid to surface drying and has reduced plastic shrinkage cracking.

2.6.4. Silica Fume (SF) Concrete in Aggressive Environments

According to T.C. Well (2004), silica-fume concrete is gaining popularity as a corrosion-protection system for parking garages, bridge decks, and other structures because it reduces chloride penetrability. Twenty-two hundred parking areas were built between the years 1979 and 1984 in the United States. With more than 100 of the larger structures being constructed on an annual basis, it is important that precautions be taken to protect them against deicing salt-induced corrosion. The latest exciting product to enter the corrosion protection market is silica fume (microsilica).

Concrete in a non-aggressive environment is a very strong, durable, and long-lasting building material. In aggressive environments, some precautions may be needed to protect the concrete or embedded steel.

Bridges and parking garages are deteriorating at an alarming rate due to chloride-induced corrosion. Bridge decks have de-icing chemicals deposited directly on the surface where the chemicals affect not only the deck but also the supporting structural members due to leakage. Although de-icing chemicals are used only sporadically in parking garages, cars carry salt-infested snow into the garages. Much of this salt remains after the cars leave.

Unlike bridges, however, which are washed by rains, parking garages are rarely washed down. The salts deposited in the winter remain all year. Indeed, when comparing concrete chloride contents of bridge decks and parking garage decks in the same location, and all other parameters being equal, the garage decks usually show a higher chloride content at all slab depths. This chloride content is due to the presence of larger amounts of chlorides on the slab surface during hot weather. As ambient temperatures rise, chlorides are able to diffuse through the concrete pores at a greater rate of speed. This phenomenon is much applicable in the Malaysian context.

The highly alkaline environment of concrete creates a protective passivating layer on steel that inhibits the electrochemical reaction of corrosion under normal conditions. Chlorides will move through the concrete pores as well as through the transition zone between the paste and aggregate and eventually reach the embedded steel. Penetration of the passivating layer takes place, and corrosion of the steel begins.

As the chloride content around the rebar increases, so does the corrosion rate. The corrosion product will expand in size by roughly four times its original volume, creating tensile pressures on the concrete up to 50MPa. The concrete eventually ruptures, causing cracking and spalling which allows more chlorides to enter at an even faster rate. Eventually, the concrete will deteriorate, requiring expensive rehabilitation or causing structural failure.

2.6.5. HPC in Marine Environment

The degradation of concrete structures due to the ingress of salts like chlorides is of obvious importance in civil engineering. M. Mohamed and M. Hamid (2002) mentioned that, structures built in an aggressive environment like coastal regions will especially be subjected to chloride attack. The chloride attack is one of the most important aspects when the durability of concrete is considered. The chloride ion ingress is the primary cause for rebar corrosion. Statistics have indicated that over 40% of failure of structures is due to the corrosion of steel (M.S. Shetty, 2007). Thus, chloride induced corrosion of reinforcement is the most destructive form of damage affecting durability and serviceability of concrete.

G. Schutter (2004) discovered that chloride can be introduced into concrete via internal sources (from cement, aggregate, water and admixture system) and external sources (from environment). Due to chloride ingress the alkaline passive layer present around the rebar is destroyed and initiates corrosion.

Nowadays durability properties play an equal role as strength. The strength and durability of concrete was enhanced by adding mineral admixtures like fly ash, rice husk ash, in concrete. This enhancement of strength and durability is due to the improvement of micro-structure of cement paste like porosity, permeability and sorptivity (A.K. Tiwari, 2004). The development of concrete using silica fume improves the early age performance of concrete.

2.6.5. HPC – Service Life and Cost Consideration.

P.C. Aitcin (2000) mentioned that it is sufficient to look at the very poor appearance of many present infrastructures, and the numerous repair works that are consuming so much time and money. It is bad to have them demolished when they have only reached half of their intended life cycle. The enormous socioeconomic costs associated with various maintenance repairs (deviations, traffic jams, loss of time and pollutions) are also the major problems.

The price of 1 m^3 of reactive powder concrete is very frightening to engineers who still compare this price to the price of 1 m^3 of HPC. Logical comparisons should be applied and practiced. Thus HPC contributes to high early strength, with cost consideration and quote says;

2.7 Effects of HPC on chemicals

2.7.1. Admixtures

F.M. Lea (1971) states that, properties of concrete, in both the fresh and hardened states, can be modified by adding certain materials to concrete mixtures, those materials are known as admixtures. Admixtures vary widely in composition, from surfactants and soluble salts to polymers and insoluble minerals.

Generally, they are used in concrete to improve workability, accelerate or retard setting time, control strength development, and enhance the durability to frost action, thermal cracking, alkali-aggregate expansion, sulfate attack, and corrosion of the reinforcement.

Admixtures can be divided into two types as follows:

i. Chemical admixtures - Materials in from of powder or fluids that are added to concrete to give it certain characteristics not obtained with plain concrete mixes. in normal use, admixtures dosages are less than 5% by mass of cement and are added to concrete at the time of mixing .(i.e. $CaCl_2$, Plasticizers , Corrosion inhibitors etc).

ii. Mineral admixtures - Inorganic materials have pozzolanic or latent hydraulic properties. They can be added to improve the properties of concrete or as a replacement for OPC, such as silica fume and fly ash.

2.7.2 Cement Replacement Materials

From F. Edward and A.W. Charles (2001), there are a number of good reasons to replace a portion of the ordinary Portland cement (OPC) in high performance mixtures with pozzolans and alternative cements. From an economic standpoint, reducing the cost of the raw materials in a cubic yard of concrete by replacing cement with pozzolans and alternative cement is an attractive proposition because it will reduce the overall cost of the project.

In addition to the cost savings the use of alternative cementatious materials saves the energy that will be used in producing the cement replaced, reduces the production of carbon dioxide gas, CO_2 and maximizes the value and use of by-product materials.

The three most often used materials to replace OPC are silica fume, fly-ash and slag. All three of these materials are by-products of other material processes. There are even more attractive features of these replacement materials. They are better than OPC in improving some of the important properties of the finished concrete material.

One of the primary reasons to use HPC is to increase the strength of concrete. The most famous by-product used as replacement is still Silica Fume (SF) and has successfully proven itself to be a wonderful strength enhancer.

S.P. Shah and S.H. Ahmad (1994) mentioned that most modern high strength concrete contains one supplementary cementing materials. However, to cater for some unexpected and unavoidable incidents, a substitution of the cementing material has to be available. Here in this research the Microwave Incinerated Rice Husk Ash (MIRHA) suits the acceptance limits (chemical requirements of silica 85%) for silica fume (SF) as indicated in Table 2.1, 'Canadian Specifications for Silica Fume' taken from CSA Standard A23.5.

Table 2.1 - 'Canadian Specifications for Silica Fume' CSA Standard A23.5

Canadian Specifications on Silica Fume - CSA Standard A23.5	
Chemical Requirements	
SiO2, min (%)	85
SO3, max (%)	1
Loss in ignition, max (%)	6
Physical Requirements	
Accelerated pozzolanic activity index , min (%) in control	85
Fineness, max (%) retained on 45μm sieve	10
Soundness - autoclave expansion or contraction (%)	0.2
Relative density, max variation from average (%)	5
Fineness, max variation from average (%)	5
Optional Physical Requirements	
Increase in drying shrinkage, max (%) of control	0.03
Reactivity with cement alkalis, min reduction (%)	80

From K. Ismail and L. Waliuddin (1996), the color of the completely burned rice husk in the microwave is blackish. This product, the burnt rice husk is known as Microwave Incinerated Rice Husk Ash (MIRHA). Investigation on the chemical properties of the MIRHA shows that the silica content is about 80% - 90%. This matches the chemical requirements of Silica Fume (SF).

P. Pavlenko *et.al* (1998) states that if cement replacing materials such as Silica Fume (SF) from the metallurgical industry is to be added into a concrete mix of reduced cement content, there is normally little or no CO2 released into the atmosphere.

2.7.3. Silica Fume (SF) in HPC

2.7.3.1. Background

SF is also known as micro silica, a by-product resulting from the reduction of high-purity quartz with coal in electric arc furnaces in the production of silicon and ferrosilicon alloys. SF is a fine powder of spherical particles with an average diameter of about 0.1 μm, which are about 2 orders of magnitude finer than particles of ordinary Portland cement.

SF also contains more than 90% silicon dioxide; thus, they are highly effective pozzolanic material to be used in concrete. A pozzolanic material contains silica in a reactive form which will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide to form compounds possessing cementatious properties (K.N. Yu *et.al*, 2000).

M.D. Luther; P.A. Smith (1991); V.M. Malhotra and K.P. Mehta (1996) reported that SF can contribute to the compressive strength development of concrete. This is because of the filler effect and excellent pozzolanic properties of the material that translate into a stronger transition zone at the paste-aggregate interface.

SF contribution to the development of compressive strength depends on various factors such as percentage of SF, water cement (w/c + SF) ratio, cement content and composition. Very fine particles of SF get absorbed on the top oppositely charged surface of cement particles and prevent them from flocculation. The cement particles are then effectively dispersed and will not trap large amounts of water, which means that the system will have a reduced water requirement for flow.

In addition to the mechanisms, particle packing effect is also responsible for water reduction. Note that OPC particles are mostly on the size of 1-50μm. Therefore physical effect of particle packing by the microfine particles of a mineral admixture will reduce the void space and correspondingly the requirement for plasticizing the system.

Microfine fillers which contain a very large proportion of very fine particles such as silica fume, it should be obvious that the filler particles themselves must be dispersed with the aid of a plasticizing agent before any benefit from the particle packing effect can materialize. The Figure 2.7 is the Mechanism of bleeding reduction in cement paste by silica fume addition.

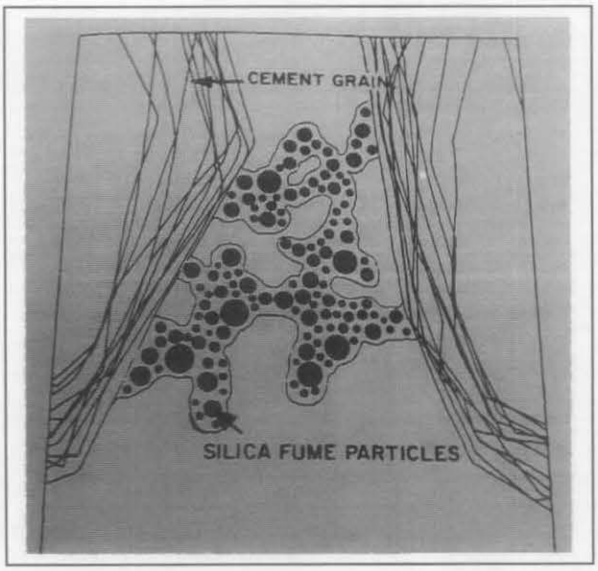


Figure 2.7: Mechanism of Bleeding Reduction in Cement Paste by Silica Fume Addition (V.M. Malhotra and K.P. Mehta, 1996).

From the research of materials conducted, the water demand of HPC with SF is directly proportional to the amount of SF used. The strength has shown very high increase as much as 15%, especially for high silica fume content at the early ages.

In general, the use of the superplasticizer is to achieve proper dispersion of the SF in concrete and to fully utilize its contribution to the strength potential. Superplasticizers are a must to be added in every HPC mixes. HPC containing SF has compressive strength development patterns which are different from those of Ordinary Portland Cement (OPC) Concretes.

If compared with those of fly-ash concretes, the effect of the pozzolanic reactions of the former is very evident in the earlier ages. This is because SF is a very fine material with very high amorphous silica content. The dosage of SF is obviously an important influence to the compressive strength of the concrete. For general construction, the optimum dosage generally varies between 7% and 10%, however, in specialized condition; up to 15% of the SF is incorporated successfully in concrete. The proper selection and proportion of cement also plays an important role in developing mixture proportions for high quality and improved HPC. The microscopic picture of the SF by A. Dunster (2009), can be observed in Figure 2.8.

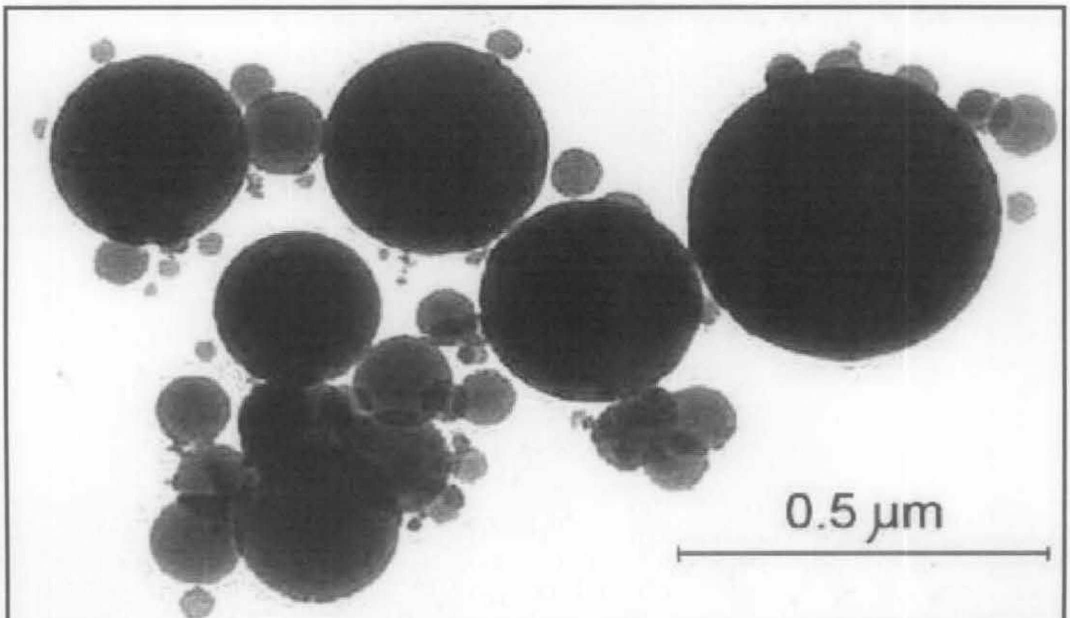


Figure 2.8 – Electron Micrograph of Silica Fume (SF), (A. Dunster, 2009)

2.7.3.1. Environmental Benefit of Silica Fume (SF)

According to D. Corning (2007), SF is aligned with the Eco-Design Principles which can be identified as below;

Principle 1: Minimize waste and consumables
Principle 2: Enable resources conservation by customers and end-use consumers
Principle 8: Create value from waste

In terms of health, environment and social benefits, SF extends construction life, resulting in resource savings and indirectly converting a waste product into a useful, marketable product. SF also increases the compression and abrasion resistance of HPC and protects it from the attack by other chemical elements. In the refractory business, SF increases high temperature strength and thermal conductivity in castables.

SF can also act as a Radon retardant. Radon is a radioactive gas that can be generated from concrete. Its concentration is enhanced in indoor environments and tracheobronchial deposition of radon progeny can lead to lung cancers. Aggregates particularly granites, are known to be the radon source in concrete (K.N. Yu *et.al.* 2000)

For building materials, such as concrete, the variation in moisture will not be very large. The main source of indoor radon for grounded houses is the soil underneath the building, while that for building constructions, it is the concrete used as a building material taking into consideration of the urban and marine environments as it was understood that radon from concrete effectively came from the aggregates mostly in granites.

When aggregates that contained mostly granites were used in concrete, improves the mechanical and chemical properties of concrete. First, due to its extreme fineness, it can effectively set the aggregate-cement paste interface, lower the porosity in the interfacial transition zone, and also effectively fill up the voids between cement grains. Second, because it is highly effective pozzolanic material, micro silica reacts with calcium hydroxide present in the hydrated Portland cement to produce additional calcium silicate hydrates.

As a result, the addition of micro silica is effective in improving the performance of concrete with a considerable improvement in ultimate strength in producing high-strength concrete and reduces the porosity of both the matrix and the aggregate-paste transition zone. The ability for the silica fume particles to lower the porosity of both the matrix and the aggregate-paste transition zone immediately suggests its ability to retard radon emission from the aggregates and radon exhalation from the concrete.

2.7.4. Superplasticizer in HPC

P. Bartow (1992) discovered that superplasticizers are based on two types of polymers, namely the salts of formaldehyde naphthalene sulphonate and formaldehyde melamine sulphonate. Superplasticizer increases the workability of the concrete without undesirable side effects compared to ordinary plasticizers. The fluidifying action of the super-plasticizer is similar to the ordinary plasticizers. It also involves the adsorption of the macromolecules of the polymer onto the grains of cement and changes the electrostatic charges on the particles.

The superplasticizer normally consists of long-chain polymer molecules of different molecular weight with a maximum of up to approximately 30 000. Investigations by M. Basile *et.al* (1999) suggested that within the range of molecular weights of the naphthalene sulphonate condensation products investigated the effectiveness of the admixture was governed by the content of the monomer and the fraction with the lower molecular weight. Increase in the molecular weight of the polymer increases the consistency of the paste measured by 'slump'.

The amount of polymer absorbed on hydrated cement changes the electrical charges and decreases the air-entrainment up to the molecular weight of about 600. There was very little change for molecular weights greater than 600. The super-plasticizers also generate some air-entrainment which affects consistency of cement paste.

A high dosage of super-plasticizers permits greater water reduction. The amount of reduction can vary from 20% to 25% depending on the circumstances. The increase in workability can be so great that fresh mixes of moderate HPC can be converted into collapsed slump. The increment also shows increase in mobility and compactability. Stability (segregation, bleeding) tends to remain either the same or slightly reduced. Normal doses of the super-plasticizing admixture do not produce an unacceptable bleeding but overdoses and inappropriate grading of aggregates can lead to substantial bleeding. In such cases a layer of laitance forms on the surface of concrete and the mix stiffens very rapidly.

It is possible that the separation of water leaves behind cement particles with absorbed layers of polymer but little free water, thus increasing greatly the viscosity of the cement paste. The rapid stiffening can be so great that fresh concrete mixes will not become plastic even when vibrated with the vibrator apparatus.

The effects of the plasticizing and superplasticising agents are related for concrete of OPC (Type 1) as basis. P. Bartos (1992) have certainly met the purpose of this research in determining the efficiency of OPC Type 1 in HPC. The possibility of the reduction of water binder (W/B) ratio is to offer potential for producing better high quality HPC. A very high dose of ordinary lignosulphonate based plasticizer increases the slump thus increasing the workability of HPC thus producing high compressive strength in early period through the optimum amount of OPC Type 1.

S.P. Shah and S.H. Ahmad (1994) concludes that there is no a prior way of determining the required superplasticizer dosage but in the end, is it done by some sort of trial and error during the mixing procedure.

Basically if the strength is the priority criterion, as mentioned in this research, the lowest water cement ratio (w/c) ratio should be worked on with the highest superplasticizer rate that is to be adjusted during the concrete mixing process. In general, some intermediate position must be found so that the combination of strength can be optimized.

Aberdeen Group (1987) reported that using SF in concrete requires using another innovation in concrete technology: superplasticizers, or high-range water-reducing admixtures. SF has little use without them because its water demand is so high when used alone. This is because SF is about one hundred times finer than OPC. Just as with aggregates, decreasing particle size increases surface area and the water demand. Without a superplasticizer, silica fume dries up the mix. The extra water required to get a reasonable slump would increase the water-cement ratio, thus reducing strength and durability.

SF products are available with and without superplasticizers. If a product without a superplasticizer is used, addition must be made. Recommended admixtures to use must always be referred to SF supplier. If a product contains superplasticizer, it may be necessary to add more of the admixture or a standard water-reducing admixture to get the performance required. Always check with the silica fume supplier to ensure that the admixture required to use is compatible with that in the product.

During the addition of SP, the amount that are used in conventional concrete will be more as there is a huge surface area in the silica fume that must be wetted. For best results, the superplasticizer should be added at the batch plant. A 4- to 6-inch slump should be obtained at the batch plant to ensure adequate mixing of the silica fume into the concrete. If necessary, final slump adjustments can be made at the jobsite by adding more admixture and not water.

2.8. Marine Coastal Environment

W.S. Ha *et.al* (2008) discovered that it has become increasingly apparent that attack by aggressive agents such as chloride ions, leading to corrosion of embedded steel, may cause a structure to deteriorate. Thus, the corrosion of reinforcing steel in concrete structures due to chloride transport in marine environment has received increasing attention in recent years because of its widespread occurrence and the high cost of repair and maintenance.

In tropical countries such as Malaysia, the chloride content in the sea water is increasing due to factors such as climate temperature and the salinity. This phenomenon mainly takes place in jetties and offshore platform structures where corrosion in reinforcing steel happens due to the trend of the wide use of reinforced concrete in semi-permanent structures.

Marine concrete structures are subjected to very severe exposure conditions and their durability is directly related to the quality of concrete used. For these applications, the concrete mix must have low permeability/porosity characteristics and with proper mix compositions have good durability (R.S. Ravindrarajah *et.al*, 2002).

K.P. Mehta and P.C. Aitcin (1990) defined HPC as a material which is not only characterized by high strength but also having high dimensional stability. Dimensional stability means having reduced shrinkage and creep of concrete. This is obtained by limiting the total cement content in concrete and using good quality and well proportioned coarse aggregates. It is strongly suggested that SF is to replace and also to be added. This is to improve in achieving high early strength and long-term durability.

The Silica Fume Association (SFA, 2005) emphasized that the corrosion of reinforcing steel is very significant and costly and cause the concrete deterioration. It doesn't matter whether the chloride comes from the ocean or from de-icing salts from the sea water the repair and maintenance is very expensive. Thus concrete with SF is used widely in applications where it is exposed to salts from any source. Reduced permeability/porosity prolongs the lifespan of the structure. A schematic process of the corrosion can be observed in Figure 2.9.

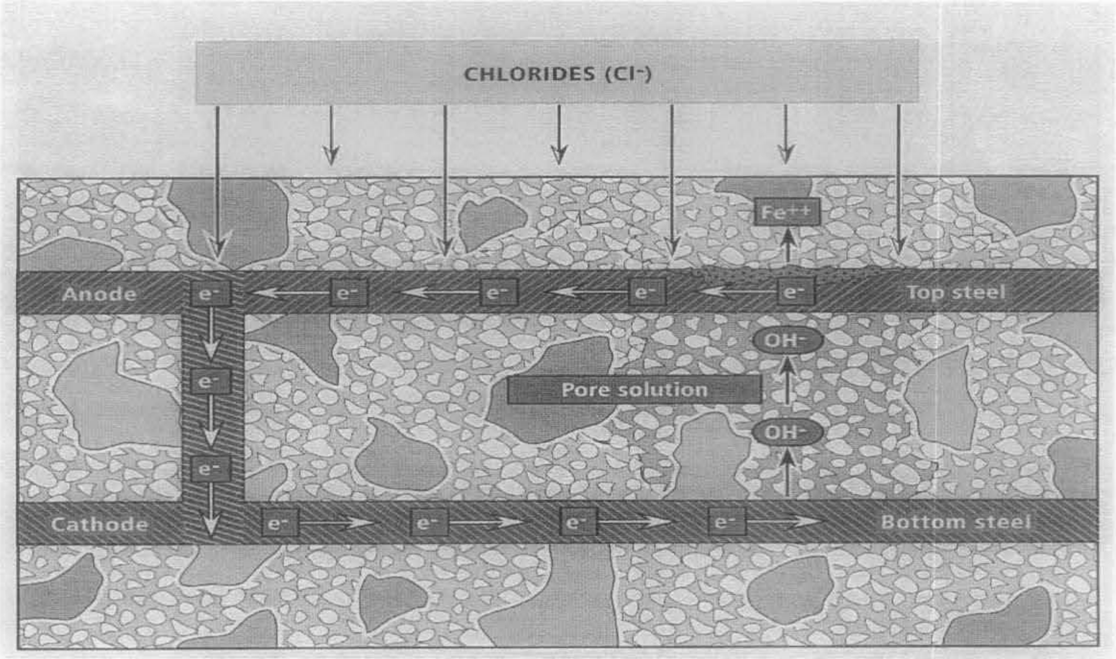


Figure 2.9: Schematic of Corrosion Process in Reinforced Concrete (Silica Fume User's Manual, Silica Fume Association, SFA, 2005).

W.D. Callister Jr. (2003) mentioned that there are three environmental zones of marine exposure are summarized below.

1. Marine atmosphere, ATM concrete placed 3 m or more above the highest maximum water level. Concrete exposed to marine atmosphere can, if relevant, be subdivided into leeward and windward marine atmosphere.
2. Marine splash, SPL. Concrete placed between 3 m above the highest maximum water level and 3 m below the lowest minimum water level inclusive of waves.
3. Submerged in seawater, SUB. Concrete placed 3 m or more below the lowest minimum water level inclusive of waves.

The illustration of the zones are shown in Figure 2.10.

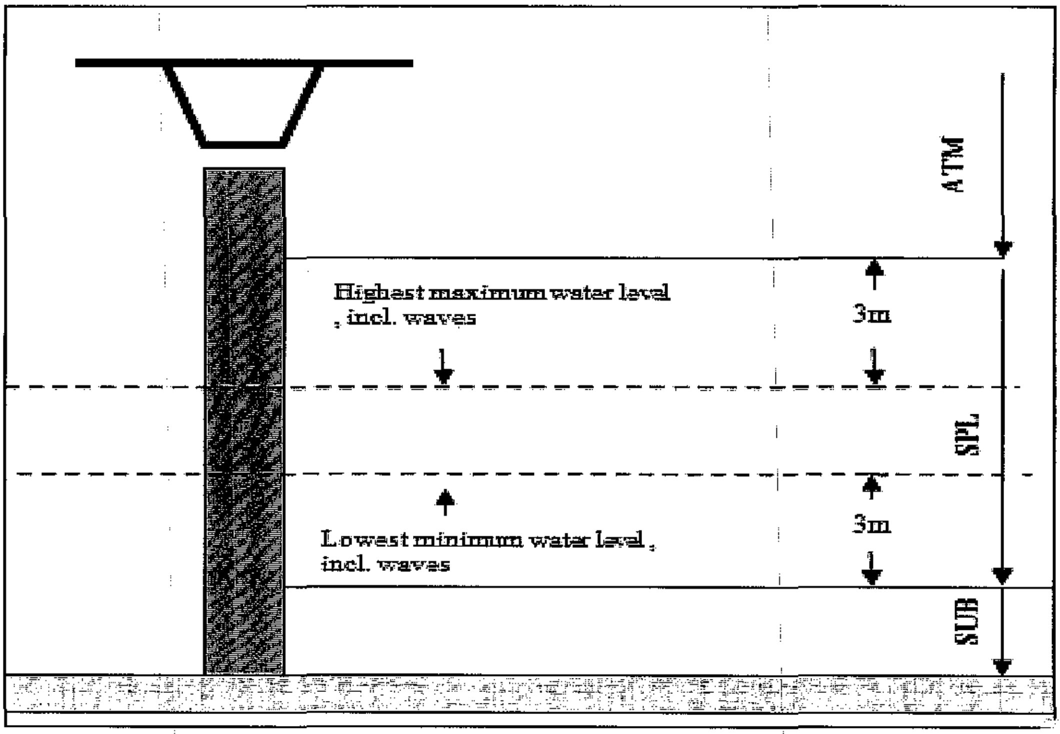


Figure 2.10: Various local marine environments. (W.D. Callister Jr., 2003)

2.8.1. Seawater

Most seawater is fairly uniform in chemical composition, which is characterized by the presence of about 3.5 percent soluble salts by weight. The ionic concentrations of Na+ and Cl− are the highest, typically 11.00 and 19.80 g/liter, respectively.Table 2.2 shows that seawater contains substances which are aggressive against concrete and its steel reinforcement (mainly chloride).

Table 2.2: Average Composition of Seawater, (H. Kejin, 1997)

Ions	Concentration (g/liter)
Na^+	11.00
K^+	0.40
Mg^{2+}	1.33
Ca^{2+}	0.43
Cl^-	19.80
So_4^{2-}	2.76

The presence of magnesium sulphate in the seawater may influence the diffusibility of the concrete by forming a coating of brucite; $Mg\ (OH)_2$.The presence of certain gases near the surface of seawater or in seawater plays an important role in the chemical and electrochemical phenomena influencing concrete durability.

Concrete exposed to sea water is susceptible to its corrosive effects. The effects are more pronounced above the tidal zone than where the concrete is permanently submerged. In the submerged zone, magnesium and hydrogen carbonate ions precipitate a layer of brucite, about 30 micrometers thick, on which a slower deposition of calcium carbonate as aragonite occurs. These layers somewhat protect the concrete from other processes, which include attack by magnesium, chloride and sulfate ions and carbonation (B.C. Gerwick, 1986)

Marine growth involving branches and mollusks is frequently found on the surface of porous concrete whose alkalinity has been greatly reduced by leaching. G.C. Hoff (1986) also mentioned that marine growth can also be a problem because it can produce increased leg diameter and displaced volume which would result in increased hydrodynamic loading.

B.C. Gerwick (1986) and G.C. Hoff (1986) also discovered that the additional surface roughness provided by the marine growth will increase the drag coefficient and will enhance the hydrodynamic loadings.

2.8.2. Temperature of Seawater

According to G.C. Hoff (1986), for concrete structures located in a warm climate, the heat may be an aggravating factor because heat is a driving energy source which accelerates both the onset and the progress of deterioration mechanisms. For each increase of 10 degrees Celsius in temperature, the rate of chemical reactions is doubled, which have a considerable impact on the rate of deterioration of concrete structures. The surface temperature of seawater varies widely from a low of -2°C in cold regions to a high of 30°C in tropical areas. The temperature of seawater determines the rate of chemical and electrochemical reactions in concrete.

2.9. Concrete for the 21st Century

2.9.1. Concrete's Carbon Footprint

Many scientists currently think at least 5 percent of humanity's carbon footprint comes from the concrete industry, both from energy use and the carbon dioxide (CO_2), the by-product from the production of cement, one of concrete's principal components.

Several studies have shown that small quantities of CO_2 are later reabsorbed into concrete, even decades after it is placed, when elements of the material combine with CO_2 to form calcite. The Environmental Engineering Committee, EEC (2009) suggests that the re-absorption may extend to products beyond calcite, increasing the total CO_2 removed from the atmosphere and lowering concrete's overall carbon footprint.

Researchers have known for decades that concrete absorbs CO_2 to form calcite (calcium carbonate, $CaCO_3$) during its lifetime, and even longer if the concrete is recycled into new construction--and because concrete is somewhat permeable, the effect extends beyond exposed surfaces. While such changes can be a structural concern for concrete containing rebar, where the change in acidity can damage the metal over many decades, the $CaCO_3$ is actually denser than some of the materials it replaces and can add strength.

"Understanding the complex chemistry of carbon dioxide absorption in concrete may help us develop processes to create the dream concrete of the 21st century. Perhaps this could help us achieve a nearly net-zero carbon footprint. Research relating to climate change is a priority." (H. Haselbach, 1997).

2.9.2. Admixtures of Tomorrow

As reported by P.C. Aitcin (2000), admixtures will be more numerous and will more often be made especially for concrete. They will be more pure, specific and precise in their action. It will be an essential component in concrete making with not a new constraint.

2.9.3. Binders of Tomorrow

The binders of tomorrow will contain less clinker where it will not be having such high C_3S content. They will have to fulfill tighter standard requirements and need to be consistent in their properties because the clinker will be having low cement content. It will also be more compatible with the complex admixtures that will result in more durable and stronger concrete. Thus quality and being inexpensive is very important to be in the consideration of various parties.

2.10. Overall Chapter Summary

The cement production and concrete consumption are increasing rapidly every year. The environmental impact delivered from the concrete industry has been a major debate. New eco- friendly concrete mixes are very high in demand. Research has shown that in order to produce good concrete mixes that caters for the building constructions in the urban and marine environment, ideal concrete mix designs need to be developed, mechanical properties in terms of aggregates need to be understood and demands from the construction industry for high strength building materials need to be fulfilled. Not only that the Earth's ecosystem needs critical consideration and balanced in effort to produce 'Eco-Friendly' concrete mixes; low cement consumption, low cost, low energy consumption and durable in various construction environments. To cater for such vision, in this research, waste chemical known as Silica Fume (SF) was used. It was known as the cement replacement material where it replaces OPC (Type 1) and is ideal in contributing in very high early age strength in design mixes. In addition, superplasticizer is used and is added into mixes through the trial and error method. The performance of the concrete mixes is to be investigated in fresh and hardened conditions. The engineering properties of the concrete mixes includes fresh properties; slump and hardened properties; compressive strength, total porosity, flexural capacity, tensile capability and chloride penetration ability in marine environment.

2.11. Design Development.

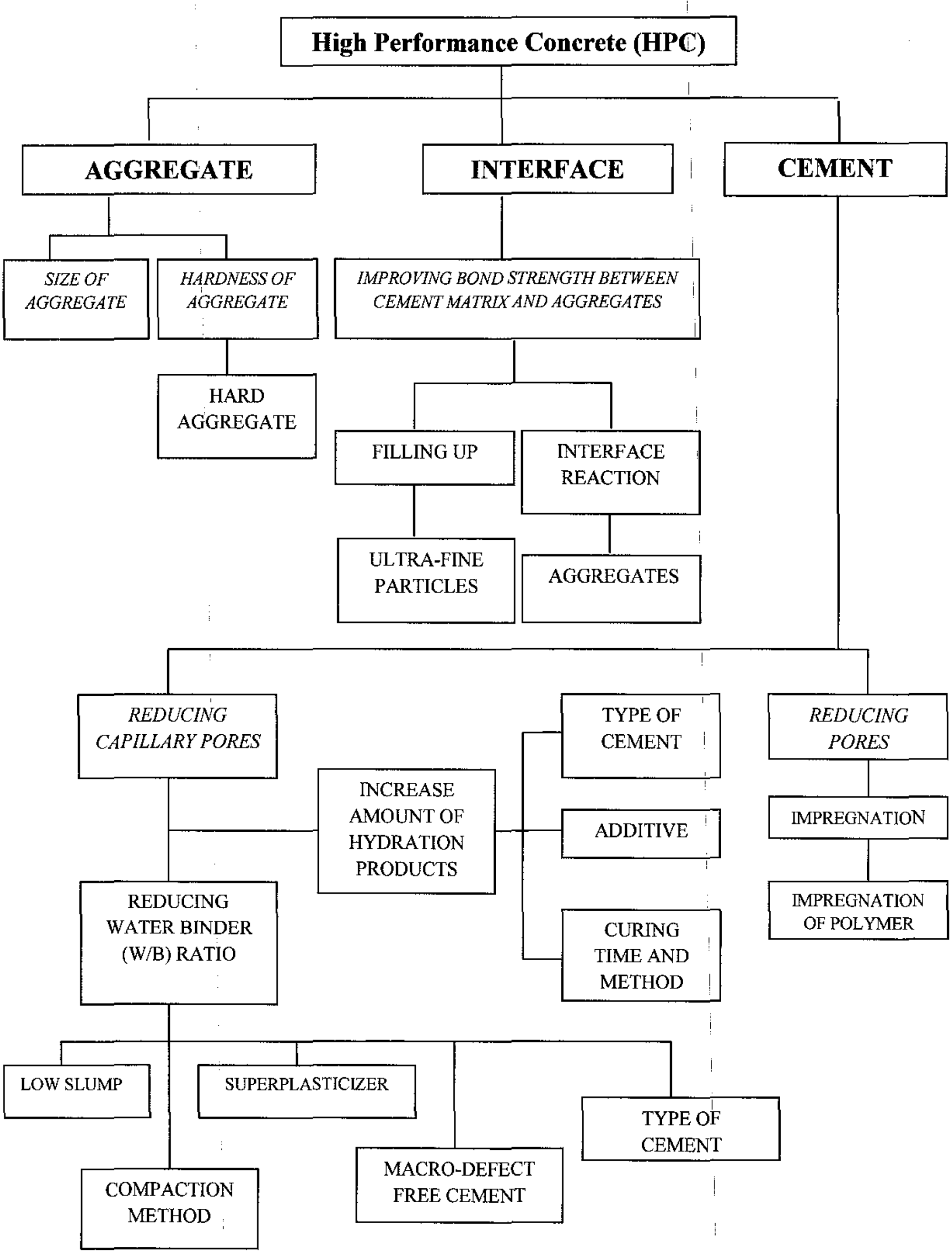


Figure 2.11: Design Development (HPC)

CHAPTER 3

EXPERIMENTAL INVESTIGATIONS

3.1. Overview of Chapter

This chapter mainly discusses the experimental approaches which are used in this research. The main focus of this research is the mix design procedures that were conducted to utilize the full efficiency of the constituent materials so that the ultimate concrete would be a green concrete. Figure 3.1 shows flow of the project.

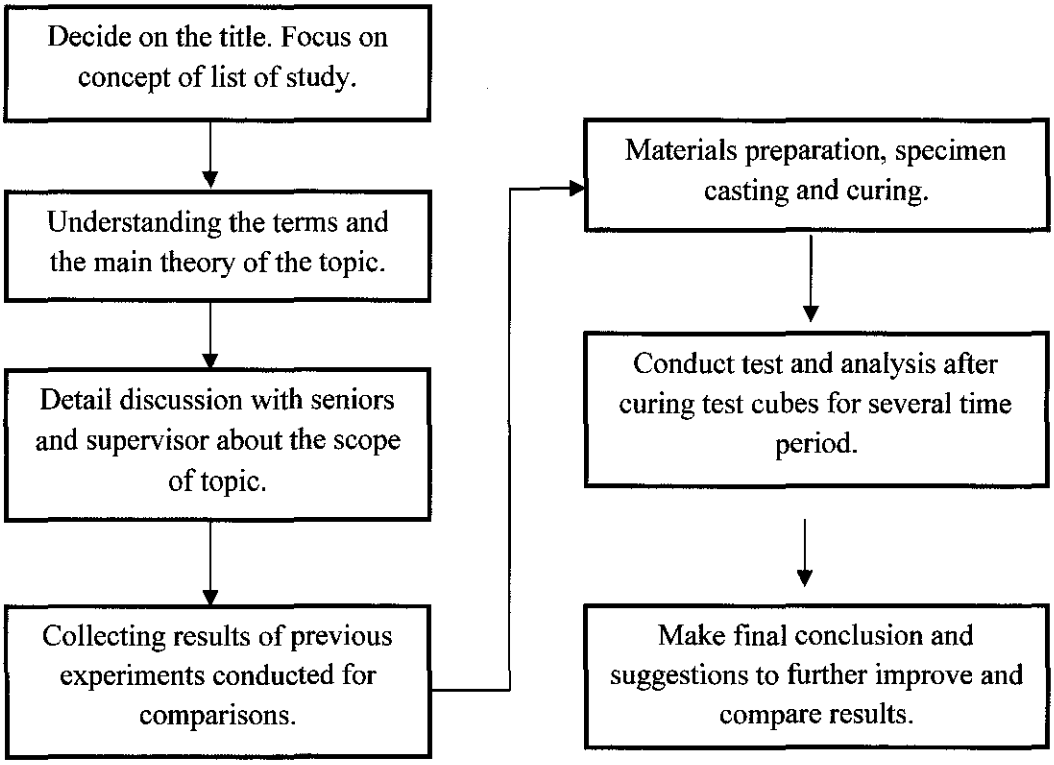


Figure 3.1: Project Flowchart

3.2. Concrete Mix Designs.

The concrete mix design process aims to determine the optimum proportions of the components of concrete in order to achieve the intended requirements throughout the life of concrete structure. For developing concrete mix design, three important stages of concrete are considered; the fresh concrete, the early age of hardened concrete of first 28 days and the entire service life.

These three stages of concrete are accessed by the five clusters of the concrete properties which consist of workability, consistency, density, strength and durability. These five clusters have complex and non-linear relationship among each other. Due to the number of complexities involved, a trivial approach for mix design proportion is adapted that is based on material selection and their properties, types and nature of construction and many other considerations.

For this research, a trial mix design approach was adapted focused to maximize the efficiency of all constituent materials such as aggregates, cement, and additives. With that approach, the end product (concrete) was obtained as the environmental friendly and green concrete. In the following sub-sections, material properties and trial mix design procedures are discussed.

3.2.1. Material Properties and Selections

In order to achieve the highest efficiency of concrete and all its constituents, the experimental investigation is based on 5 components of the concrete system as below:

1. Aggregates (Fine aggregates and coarse aggregates)
2. Cement (Ordinary Portland Cement (OPC) Type 1)
3. Cement Replacing Materials (CRM). For this research, Silica Fume (SF) was chosen as the CRM.
4. Water
5. Superplasticizer

The properties and the characteristics of the materials used are discussed in the next sections. Materials used in this research were selected according to the specifications that were suitable with the objectives of this research and meet the requirement of the appropriate standards that is the British Standards and ASTM Standards.

3.2.2. Trial Mix Proportions.

The main focal point of the mix proportion was to maintain the maximum cement content within the range of 250 kg/m³-400 kg/m³ obtained from various research catering for lower and higher range of cement consumption that would be able to achieve 28 days cube strength between 50 MPa-80 MPa as it was highly demanded by contractors in the construction industry. The details of the trial mix proportions are given in Table 3.1.

Table 3.1: Details of Trial Mix Proportions

Mix Series	OPC (kg/m³)	FA (kg/m³)	CA (kg/m³)	WATER (kg/m³)	SF (%)	SP (%)
250CM	250	860	1290	125	0	3
250SF5	250	860	1290	119	5	3
250SF10	250	860	1290	113	10	3
275CM	275	850	1275	138	0	3
275SF5	275	850	1275	131	5	3
275SF10	275	850	1275	124	10	3
350CM	350	840	1260	175	0	3
350SF5	350	840	1260	166	5	3
350SF10	350	840	1260	158	10	3
400CM	400	830	1245	200	0	3
400SF5	400	830	1245	190	5	3
400SF10	400	830	1245	180	10	3

From the trial mix proportions, each type of concrete mixes included a control mix which contains 100% OPC, 5% SF and 10% SF. The dosages were chosen based on several literature reviews and previous research conducted so to confirm with the objectives of this research. The materials mainly cement (OPC Type 1), sand (fine aggregates) and gravels (coarse aggregates) was proportioned by weight ratio of 1:2:3. The w/c used was 0.5 (by weight) throughout the research to look upon the overall range of performance of the concrete. SP is fixed at 3% of the total mix. The slump in this research was observed and was expected to be in the range of ±50-70 mm for HPC (Silica Fume Society Association, 2008).

3.3. Materials Preparations.

In the following sub-sections, the mechanical, physical and chemical properties of materials used in this research are discussed. Besides this, materials preparations are also discussed. The preparations included tests that were conducted according to the appropriate standards procedures.

3.3.1. Aggregates (Fine aggregates and coarse aggregates)

The coarse aggregates used were gravels of nominal maximum sizes 20mm while the fine aggregates used were natural sands having 3.35mm nominal maximum sizes. Both aggregates were selected conformed to BS882:1992. for this research. Coarse aggregates were prepared as Saturated Surface Dry (SSD) aggregates by washing the aggregates. The wet aggregates were then left in the open air and sheltered from direct sunlight for 12 hours. Figure 3.1 shows the coarse and fine aggregates that were used in the research. Fine aggregates were divided into 2 types; 'Designed' and 'As-supplied' graded aggregates which produced 'Designed' mixes and 'As-supplied' mixes.

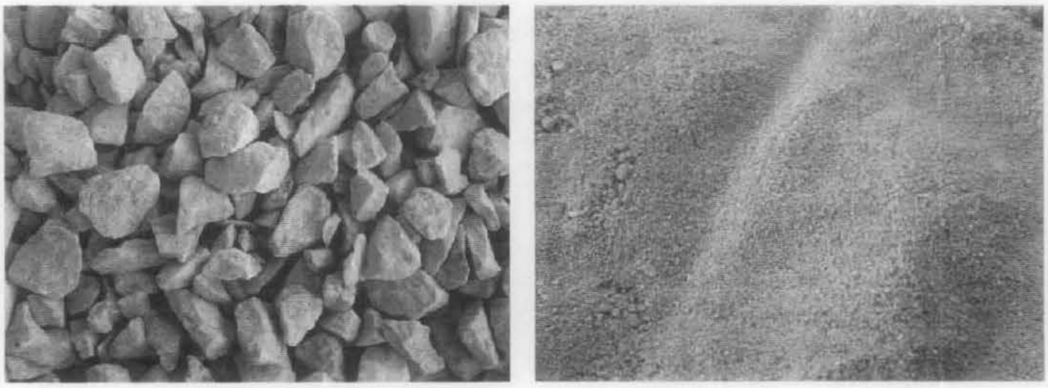


Figure 3.2: Coarse Aggregates & Fine Aggregates

In this research, quality control is also very important into obtaining quality concrete properties. The Sieve Analysis Test, X-ray Fluorescence Spectrometry (XRF) Test and X-Ray Diffraction Spectrometry (XRD) Test were conducted. The test procedures were discussed for each test.

3.3.1.1. Sieve Analysis Test

For this research, the sieve analysis is conducted with accordance to BS 882: 1992 for the fine aggregates (sand) and coarse aggregates (stones, max. 20mm). The purpose of this test is to obtain well graded and finely distributed input of raw materials so to have quality mix without taking into consideration of cement content in mixes. Thus to fulfil the main objective that well graded and finely distributed aggregates affects contribution to high strength in concrete materials, two type of mixes that is the 'Designed' and 'As-supplied' mixes were prepared.

3.3.2. Chemical Composition of OPC and SF

For this research, the chemical composition is determined for OPC and SF from two ways which were:

1. X-Ray Fluorescence Spectrometry (XRF) Test.
2. X-Ray Diffraction Spectrometry (XRD) Test

The purpose of the tests was discussed in the following sub-sections.

3.3.2.1 X-Ray Fluorescence Spectrometry (XRF) Test.

XRF Test was conducted on samples of SF and OPC used throughout this research study. The purpose of this test is to determine the chemical composition and trace any harmful elements contained in the SF and OPC. Chemical compositions of both of these samples were obtained and analyzed.

The XRF machine, BRUKER AXS S-Pioneer (Refer to Figure 3.3) was used for this test which is supplied by BRUKER AXS as mentioned in S. Harun (2007).

Figure 3.3: XRF Machine (BRUKER AXS S-Pioneer)

3.3.2.2 X-Ray Diffraction Spectrometry (XRD) Test

The XRD Test was carried out using Diffractometer of Bruker Axs D8 Advance to analyze the crystalline properties of SF sample and to detect the presence of various crystal system of SiO_2 in SF. The sample was taken from SF that will be incorporated into the concrete mixture. The XRD results were used to describe the effect of SF into the concrete properties during the maturing period. The X-Ray Diffractometer used in this research in Figure 3.4.

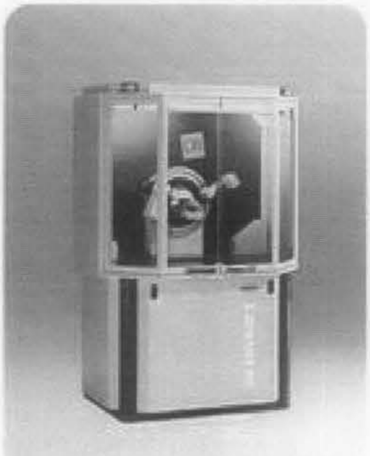


Figure 3.4: Bruker Axs D8 Advance Diffractometer

3.3.2. Ordinary Portland Cement (OPC) Type 1

Ordinary Portland Cement (OPC) Type 1 which conformed to the requirements of BS EN 197-1 2000 was used with the physical and chemical properties listed in Table 3.2. OPC Type 1 was preferred because the observation on concrete properties can be done in normal hydration process hence the advantages of SF usage in concrete can be optimized.

Table 3.2: Physical and Chemical Properties of OPC Type 1.
(Cement Industries of Malaysia Berhad, CIMA)

Modulus	Lime Saturation Factor	0.96
	Silica Modulus	2.37
	Iron Modulus	1.58
Compressive Strength (N/mm^2)	3 Days	38
	7 Days	46
	28 Days	56
Chemical Ingredients (%)	SiO_2	19.98
	Fe_2O_3	3.27
	Al_2O_3	5.17
	CaO	63.17
	MgO	0.79
	SO_3	2.38
	Total Alkalis	0.9
	Insoluble Residues	0.2

3.3.3. Silica Fume (SF)

Silica Fume (SF) was supplied complimentary by SIKA Kimia Sdn.Bhd. The SF used was of the finest quality and no additives are added during the mixing and casting process. SF was obtained from Elkem materials in dry densified form with Grade 920 confirming to the mandatory requirements of ASTM C1240.

3.3.4. Water

The water used in the mix needed to be free from harmful chemicals, oil, chloride, silt or any harmful ingredients that could affect the performance of the concrete. The water used in the concrete mixes was tap water.

3.3.5 Superplasticizer

In this research, superplasticizer (SP) was supplied by SIKA Kimia Sdn.Bhd. used in a fixed dosage of 3%. SP used was high range water-reducing concrete admixtures that met the requirement of BSEN934-2:2001. It was polycarboxylate type, has the density of 1.11kg/l and pH value of 5.5. Figure 3.5 shows the superplasticizer that was used in this research.

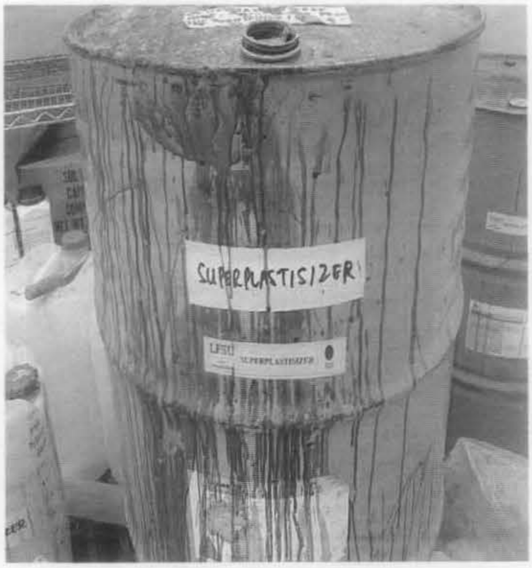


Figure 3.5: Superplasticizer

3.4. Concrete Mixing and Samplings.

The procedure of machine mixing that was used in this research was in accordance to BS1881-125:1986. Mixing of concrete ingredients was performed in the laboratory using a 105 liter capacity concrete mixer. The dry ingredients which included cement, sand and gravel was first mixed for 1 minute in the mixer prior to water addition. Cement replacing material (CRM) such as Silica Fume (SF) and superplasticizer (SP) that was diluted in water were added to the dry ingredients in the mixer. After addition of the water to the dry ingredients, it was mixed for 1 minute to achieve homogeneous concrete and then left for 8 minutes. Next cement was added and mixed for 1 minute and finally the remaining water was added into the concrete mix and mixed for another 1 minute. After the fresh concrete was mixed homogeneously, it was tested for determination of slump.

3.5. Fresh Concrete Testing.

After mixing concrete, the fresh concrete was tested for finding slump as recommended by BS1881: Part 102:1983. The mix was filled into a clean truncated mould (diameter at top: 100mm, diameter at bottom: 200mm, height: 300mm) by four equal layers and each layer was rodded 25 times with a round steel rod. After the top layer was rodded, the excess concrete at the top of the mould was wiped out. Then, the mould was lifted carefully in vertical direction and the differences between the height of the slumped concrete and mould were measured as its workability. This can be observed in Figure 3.6.

Figure 3.6: Measurement of slump

3.6. Hardened Concrete Properties.

Following sub-sections elaborates on the details of hardened concrete tests performed in this study.

3.6.1. Compressive Strength Test.

Concrete cubes were cast in standard steel mould of dimension 150×150×150 mm. Concrete in moulds were laid in three layers of approximately the same thickness. After laying each layer, compaction was done by applying vibration according to the specifications defined in BS8110: 1997. Concrete specimens were tested at the age of 3, 7, 28, 56 and 120 days.

The concrete specimens in the moulds were then covered with polythene sheet to prevent evaporation and left for 24 hours. Eventually, all concrete specimens were removed from the moulds and then transferred into the water bath at room temperature for curing until the desired age of testing.

3.6.1.1. Compressive Strength Test Procedure

The main objective of this test was to obtain the concrete strength (crushing strength). Observations were made on factors of cube density and failures.

All cubes were stripped out of the moulds after 24 hours and shifted into the curing tank. The crushing test complied with the BS: 1881, Part 4, and MS 26: 1971. Prior to the test, the cubes or specimens were weighed to obtain density and placed onto the lower steel platen plate with both smooth surfaces facing the top and bottom platen plates. The load weight was applied at the rate of 5 KN/sec. until the specimen failed. Figure 3.7. illustrates the testing arrangements.

Figure 3.7: Compressive Strength Test

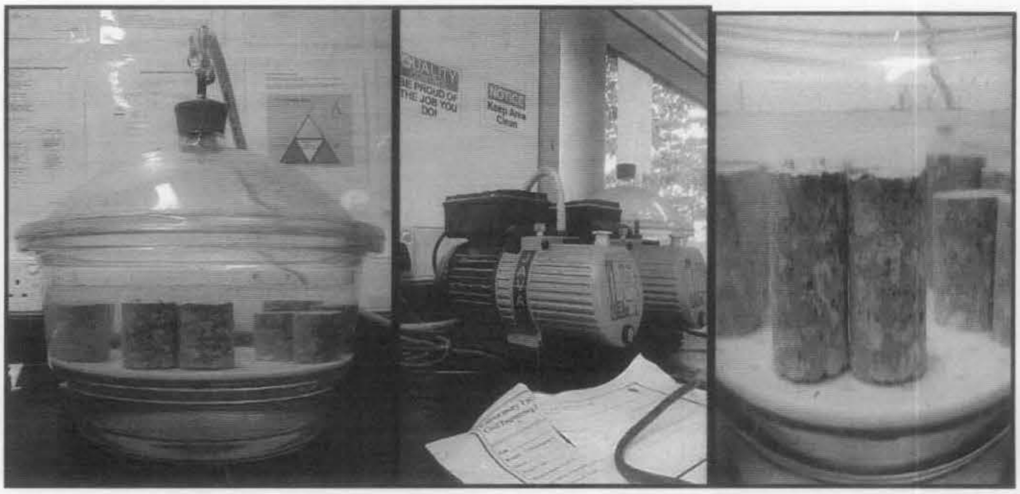
The load at the failure of concrete cube that is referred as the cube crushing load was recorded and divided by the area of the test surface i.e. 150 × 150 × 150 mm to calculate the compressive strength. At every age, three cubes were tested and the mean of value of strength was referred as the compressive strength.

3.6.2. Porosity Test.

The total porosity test was performed using vacuum saturation method (N. Shafiq, 1999). Plain concrete planks of 400×400×40 mm dimensions were cast in wooden moulds that were fabricated in Concrete Technology Laboratory in the department of Civil Engineering at Universiti Teknologi PETRONAS. 40 mm diameter cores were drilled out from the planks for total porosity measurement. The cores were then transferred into the water bath at room temperature for curing until the desired age of testing that was 3, 7, 28, 56 and 120 days.

3.6.2.1. Porosity Test Procedure

The equipment used to determine the total porosity was the vacuum saturation apparatus available in the Concrete Laboratory, Civil Engineering Department at Universiti Teknologi PETRONAS. The apparatus was similar to the method developed by RILEM (1984) for measuring the total porosity. The purpose of pressure saturation apparatus was to achieve total absorption or full saturation of dense mortar and concrete to enable the estimation of porosity. The apparatus is illustrated in Figure 3.8.



1 2 3

Figure 3.8: Apparatus for Total Porosity Test

1. Vacuum Saturation Tank
2. Pump
3. Specimens (Fully Submerged condition)

The specimens were placed in vacuum for 30 minutes in a descicator, then water was added in the descicator and immediately vacuum saturated in water for 6 hours (Figure 3.7.1). After 6 hours, pump was turned off and the specimens were left for 24 hours at fully saturated condition. After 24 hours, the specimens were weighed in the air (W_{SA}) and in the water (W_{SW}). Then the specimens were dried in an oven at 105°C for 24 hours and weighed in the air, W_d, as reported in N. Shafiq (1999). The weighing scale is shown in Figure 3.9.

Figure 3.9: Specimens weighed in air and water

3.6.2.2. Calculations of Porosity Test

The total porosity, P of concrete specimens was calculated using the following equation:

$$P = \frac{W_S - W_d}{W_S - W_W} \times 100 \quad \text{(Eq. 3.1)}$$

Where:

P	= Total porosity (%)
W_S	= Weight of saturated samples measured in the air (g)
W_W	= Weight of saturated samples measured in water (g)
W_d	= Weight of oven dry samples measured in the air (g)

3.6.3. Split-cylinder Test (Split Tensile Strength)

Concrete cylinders of 200 mm in height and 100 mm in diameter were cast, cured and tested at the age of 28 and 120 days. The test was carried out in accordance with the ASTM C39-86 Vol. 04.02, 1986. The British Standard of BS EN12390-6:2002 was also referred. The test results were used to determine the tensile strength of concrete.

3.6.3.1. Split Cylinder Test Procedure

The split cylinder test was carried out using a standard cylinder specimen by applying a line load because the sides are not smooth enough and would induced high compressive stresses at the surface. Therefore, a narrow loading strip made of soft material was used. The application can be observed from Figure 3.10.

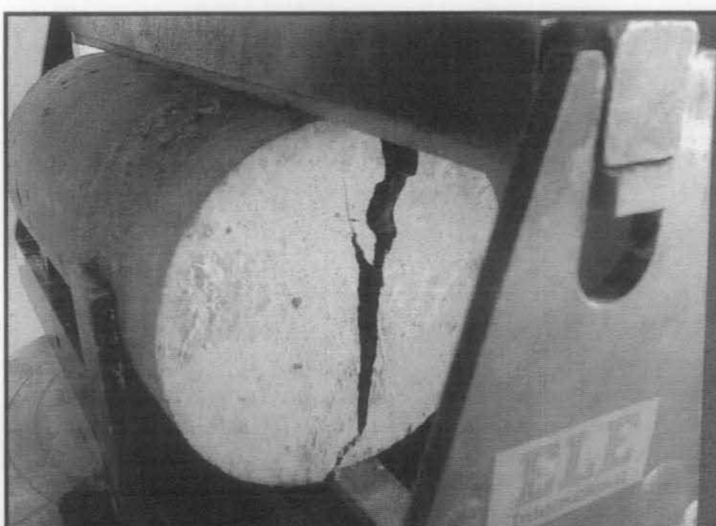


Figure 3.10: Split Cylinder Test

The stress at failure was taken as the tensile strength of the concrete. The specimens were tested by using Universal Hydraulic Testing Machine with a maximum capacity of 2000 kN. During the test, concrete cylinder was loaded with 9.4 KN/s constant loads without any sudden shock loads. The tensile strength of split cylinders was obtained from the testing machine.

3.6.4. Modulus of Elasticity (Flexural Tensile Strength)

Concrete prism of dimensions 500×100×100 mm were cast in standard moulds, cured and tested at the age of 28 days with two specimens for each testing age in accordance with ASTM C469-02el, 1986. The British Standard of BS 1881-109, 1989 was also referred. The results were used to determine the modulus of elasticity.

3.6.4.1.. Flexural Strength Test

The specimens were tested by using the Universal Hydraulic Testing machine with a maximum capacity of 100 kN. The results were as displayed by the machine. During the test, concrete prism was loaded with a point load of 9.4 KN/s without any sudden shock loads which is shown in Figure 3.11:

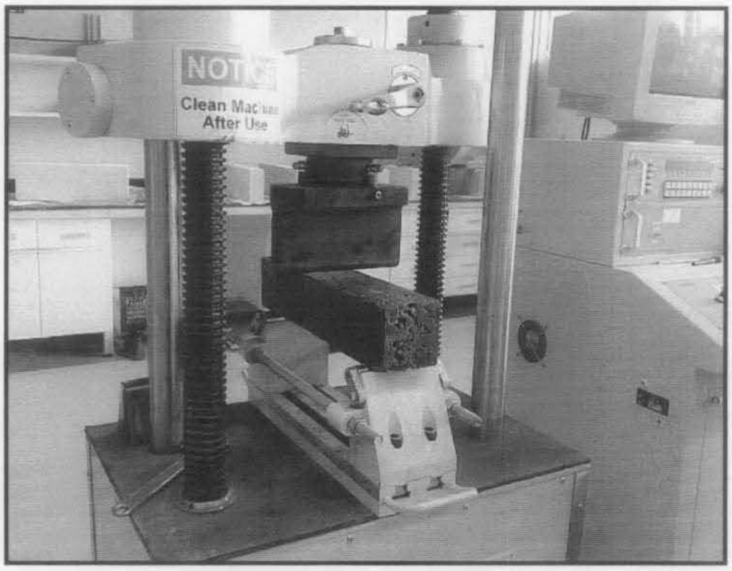


Figure 3.11: Universal Hydraulic Testing Machine

3.6.4.2. Modulus of Elasticity Calculation

Equation 3.2 was used to calculate the Modulus of Elasticity, E_f from flexural test

$$E_f = \frac{L^3 m}{4b\,d^3} \qquad \text{(Eq.3.2)}$$

Where:

- L = Support span, (mm)
- b = Width of test beam, (mm)
- d = Depth of tested beam, (mm)
- m = The gradient (slope) of the initial straight-line portion of the load deflection curve, (N/mm)

3.6.5. Chloride Migration Test (Durability in Marine Environment)

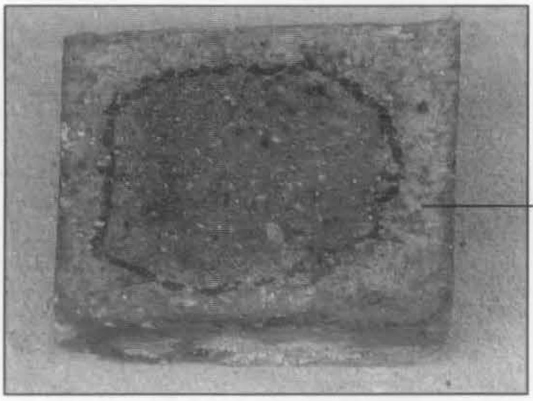
Concrete cubes of dimensions 100×100×100 mm were cast in standard moulds, cured and tested at the age of 28, 120, and 180 days. After 28 days, concrete samples are put in the oven to dry for 24 hours. They were then let to cool for half hour before being placed into the salt water. Salt water with salt concentration of 3% was prepared in a curing tank of water capacity of 200 gallons. Sea water from the sea can also be used. The test procedure was referred to N. Shafiq et.al (2007).

At the desired age for testing, the cubes were split into two halves. On the cut surface, silver nitrate solution was sprayed to distinguish the depth of salt water penetration.

3.6.5.1. Chloride Migration Test Procedure

For this research the test is desired to measure the chloride ingress in concrete samples with respect to time. Concrete samples of dimensions 100 × 100 × 100 mm were prepared.

The test was conducted by cutting the concrete sample into two pieces and sliver nitrate ($AgNo_3$) sprayed onto the surface of the broken samples. As shown in Figure 3.12, $AgNo_3$ will show the area of the concrete sample affected by the chloride diffusion. Chloride profiles were then measured. The results were obtained for the samples of the ages of 28, 120 and 180 days.



Area of Chloride Diffusion

Figure 3.12: Chloride Diffusion in Concrete

The penetration depth was measured and recorded. The results were then analyzed and appropriate graphs were plotted for better comparison. The unit measurement for the depth of chloride penetration is in millimeters (mm).

3.7. WORKSHEETS APPLICATIONS

For this research, 3 worksheets are produced using the Microsoft Excel Software to help to ease in calculations and to determine the following elements;

1. The amount of cement (OPC) used in research for every mix series in tons and kilogram (kg).
2. The efficiency of research compared to other research from the amount of cement consumption for each mix series in percentage (%).
3. The amount of carbon dioxide (CO_2) emitted from each mix series in percentage (%).
4. The effectiveness of research in CO_2 emission compared to other research in percentage (%).

The worksheets are to cater for both 'Designed' and 'As-supplied' mixes. Standard units, tables and formulas are used in the calculation processes. The examples of the worksheets can be observed in Appendix A, B and C.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1. Overview of Chapter.

The main objective of this chapter is to present the analysis and discussion on the experimental with respect to the influencing factors, trends and shortcomings. The overall discussion is divided into 3 parts; Quality Control that included the performance tests on constituent materials such as the results of sieve analysis of sand, XRF and XRD of powder material. The second and third parts contained the hardened concrete results and efficiency analysis respectively.

4.2. Quality Control.

4.2.1 Sieve Analysis of Sand.

The sieve analysis was conducted in accordance to the British Standard (BS) for the fine aggregates (sand) and coarse aggregates (stones, max. 20mm). The purpose of this test was to obtain well graded fine and coarse aggregates that offered maximum packing, hence, the hardened properties were improved. Table-4.1 shows the mix-proportion from various sieve sizes of the designed-graded sand and Table-4.2 shows the sieve analysis of the as-supplied sand. The results are plotted in the Figures 4.3 and 4.4 respectively. The designed-graded sand was selected from the previous research by N. Shafiq (1999) that was aimed to achieve the maximum packing and the minimum porosity of the concrete.

Table 4.1: Sieve analysis of 'Designed' graded aggregate

AGGREGATES	MAXIMUM ZONE (BS822)		TEST ANALYSIS		MINIMUM ZONE (BS822)	
FINE (SAND)	sieve size (mm)	% passing	sieve size (mm)	% passing	sieve size (mm)	% passing
	0.15	10	0.15	4	0.15	0
	0.30	15	0.30	8	0.30	2
	0.60	80	0.60	40	0.60	20
	1.18	90	1.18	72	1.18	50
	2.36	95	2.36	87	2.36	70
	5.00	98	5.00	92	5.00	90
	10.00	100	10.00	100	10	100
	sieve size (mm)	% passing	sieve size (mm)	% passing	sieve size (mm)	% passing
COARSE (STONES) (MAX. 20MM)	pan	0	pan	0	pan	0
	2.36	0	2.36	0	2.36	0
	3.35	3	3.35	3	3.35	0
	5.00	30	5.00	30	5.00	0
	10	80	10	80	10	30
	14	90	14	90	14	70
	20	100	20	100	20	90

Table 4.2: Sieve analysis of 'As-supplied' aggregates

AGGREGATES	MAXIMUM ZONE (BS822)		TEST ANALYSIS		MINIMUM ZONE (BS822)	
FINE (SAND)	sieve size (mm)	% passing	sieve size (mm)	% passing	sieve size (mm)	% passing
	0.15	10	0.15	0	0.15	0
	0.30	15	0.30	2	0.30	2
	0.60	80	0.60	20	0.60	20
	1.18	90	1.18	62	1.18	50
	2.36	95	2.36	87	2.36	70
	5.00	98	5.00	92	5.00	90
	10.00	100	10.00	100	10	100
COARSE (STONES) (MAX. 20MM)	sieve size (mm)	% passing	sieve size (mm)	% passing	sieve size (mm)	% passing
	pan	0	pan	0	pan	0
	2.36	0	2.36	0	2.36	0
	3.35	3	3.35	3	3.35	0
	5.00	30	5.00	30	5.00	0
	10	80	10	80	10	30
	14	90	14	90	14	70
	20	100	20	100	20	90

4.2.1.1. 'Designed' aggregate mixes

'Designed' grading was obtained from aggregates that were taken from three different parts of the main aggregate source. These mixes included the fine and coarse aggregates. The aggregate sizes and proportions were designed to suit the right measurements of the mix series designs and were used directly without any alterations during concrete mixing. The results displayed fulfilled the British Standard specifications as illustrated in Figure 4.1 and Figure 4.2.

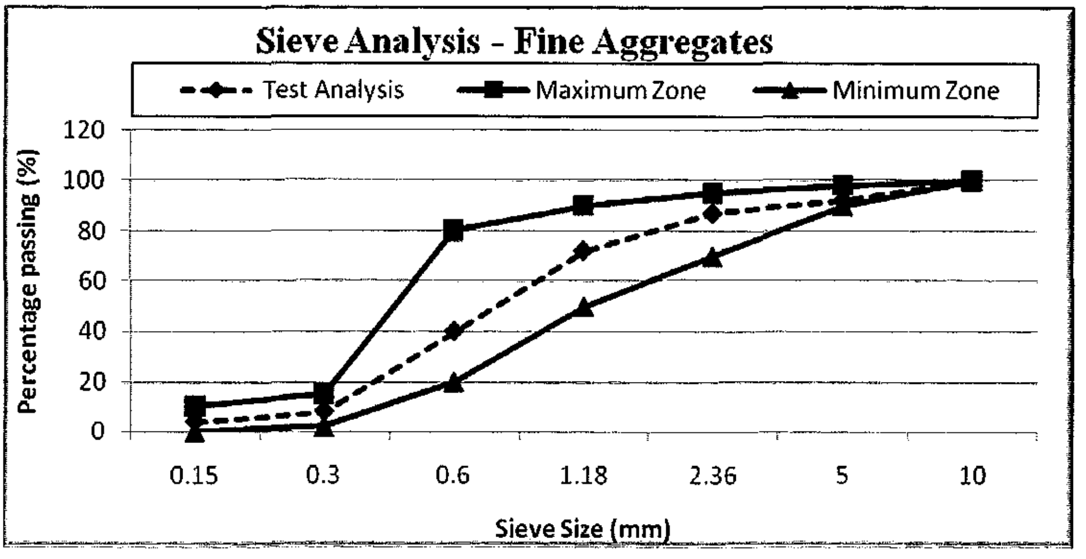


Figure 4.1: Sieve Analysis Test – Fine Aggregates – 'Designed' mixes

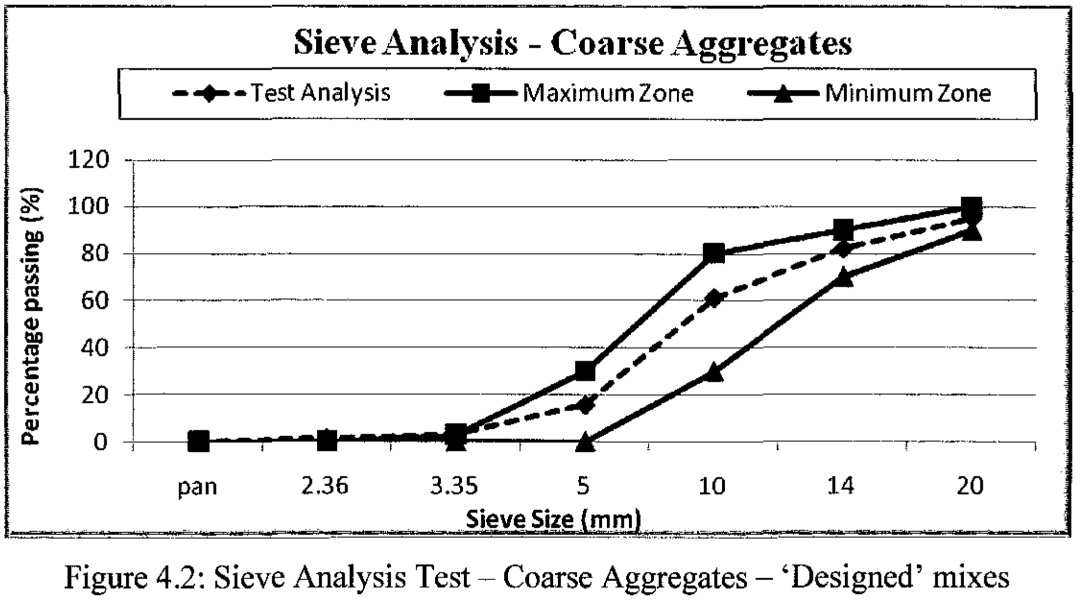


Figure 4.2: Sieve Analysis Test – Coarse Aggregates – 'Designed' mixes

Aggregates obtained and used from these mixes were well graded and finely distributed. The aggregates were good in quality, well packed and managed to reduce the risk of segregation. Less segregation of aggregates will increase the strength of concrete thus enhancing its durability (K.P. Mehta, 1999). This was so as the test analysis curve was designed to be in between the maximum zone curves and minimum zone curves.

4.2.1.2. 'As-supplied' aggregate mixes.

'As-supplied' aggregates were also obtained from three parts of the main aggregate source. The mixes also included fine and coarse aggregates. The mix proportions were designed to suit the right weight measurement but not designed with specification to the BS Standard where the test analysis curve was plotted according to results obtained from the sieve analysis test. This can be observed in Figure 4.3 and Figure 4.4.

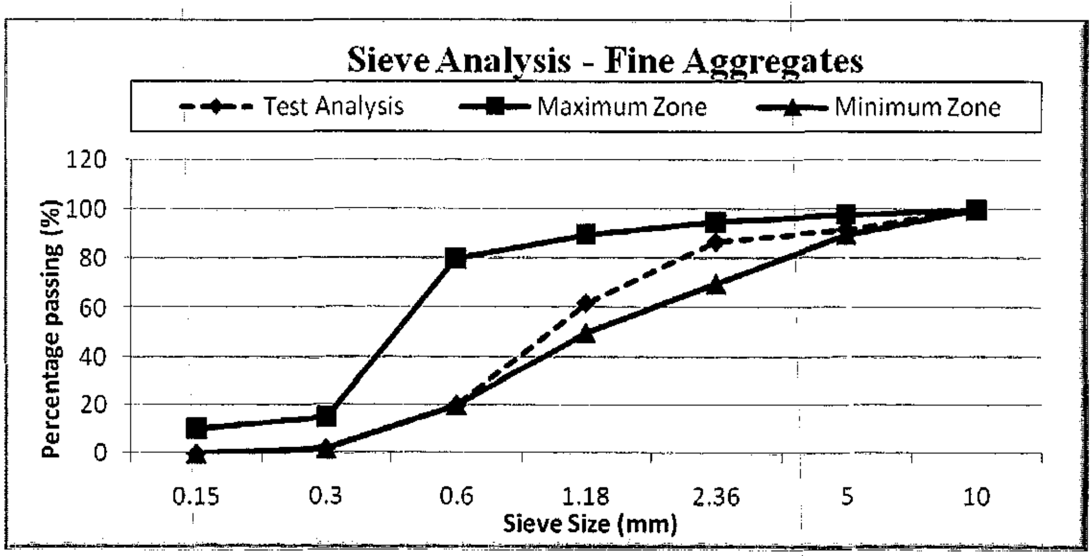


Figure 4.3 Sieve Analysis Test – Fine Aggregates – 'As-supplied' mixes

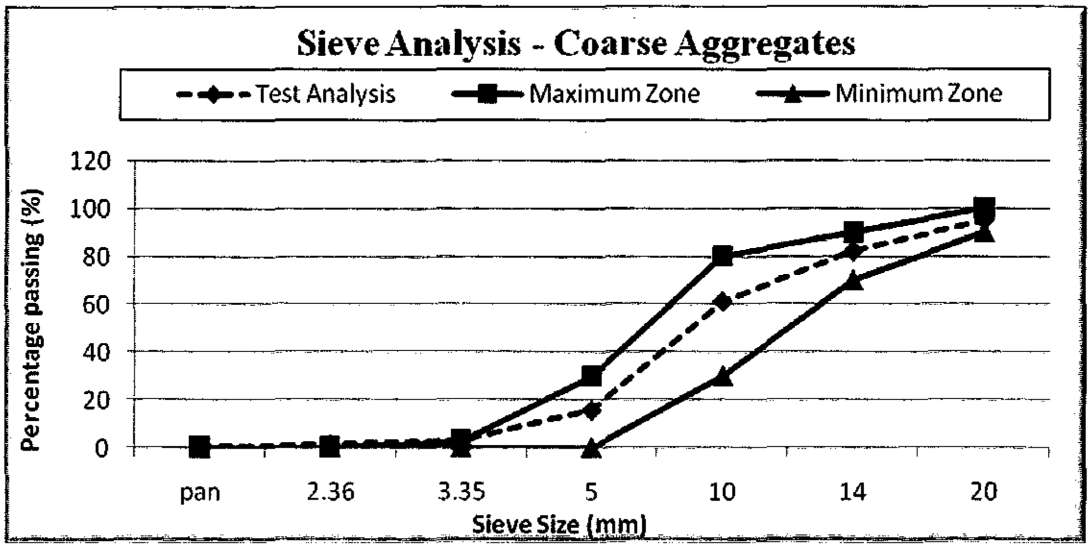


Figure 4.4 Sieve Analysis Test – Coarse Aggregates – 'As-supplied' mixes

It was found that the addition as much as 4% of sand size 0.15 mm, 6% of sand size 0.3 mm, 20% of sand size 0.6 mm and 10% of sand size 1.18mm were required to create the ideal mix design proportions. No alterations were involved for the gravels as gravels obtained were of the ideal sizes required which were of maximum 20 mm in diameter.

The test analysis curve for the coarse aggregate was within the minimum zone and maximum zone as specified by the British Standard. With alterations in fine aggregates, the main objective of the research of well graded and finely distributed aggregates in mix proportion was fulfilled. In plotted graphs shown later in the sub-sections for results discussions, the mixes were labelled as 'UD' which meant 'Undesigned'.

4.2.2. XRF Results.

XRF test was conducted on the supplied cement and silica fume to determine their chemical composition. The XRF Test was conducted and the chemical composition of Ordinary Portland Cement (OPC) Type 1 and Silica Fume (SF) is as shown in Table 4.3.

Table 4.3 Chemical composition of OPC and SF

CHEMICAL COMPOSITION	(OPC) (%)	(SF) (%)
SiO_2	21.98	91.7
Al_2O_3	4.65	1.00
Fe_2O_3	2.27	0.90
CaO	61.55	1.68
MgO	4.27	1.80
SO_3	2.19	0.87
K_2O	1.04	-
Na_2O	0.11	0.10

The pozzolanic reactivity of SF depends on the amorphous state of SF particles and the high SiO_2 content inside. XRF test is proficient in analyzing the material contents inside SF, hence the amount of SiO_2 can be observed. The oxide content of SiO_2 and K_2O are able to lower the heat evolution in concrete hydration process (C.H. Hwang, 1996). The oxide content of SF that was used for this research was the optimum composition that could give significant improvement to the concrete properties.

Wonderful characteristics were shown by SF in concrete produced from this research where with the addition of SF, very high early strength was achieved compared to normal control mix concrete (CM). This can be observed in the following sub-sections.

4.2.3. XRD Test.

The XRD Test was used to analyze the crystalline properties of a material. Graph patterns of the test shows whether the material is in amorphous, partially crystalline or in crystalline conditions. Figure 4.5 describes the properties of SF.

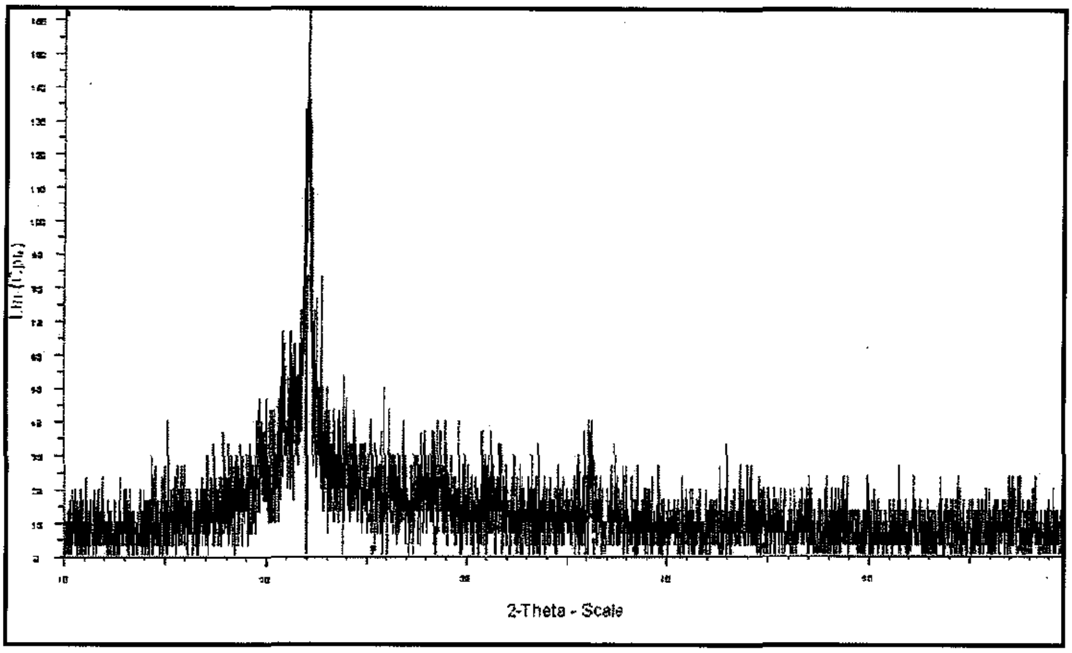


Figure 4.5: XRD Graph of SF

From Figure 4.5, the graph peaks, which appeared at the 2θ scale of 22° and 36°, indicated the presence of SiO_2 cristobalite inside SF sample. The gradual dense scatter from the XRD graph is used to indicate the amorphous state of a material. For this research the SF sample shows a sharp intensity of dense scatter where SF can be categorized as partially crystalline sample. The fully amorphous material is indicated with a smooth gradual scatter, while the fully crystalline material is indicated with a flat and sharp peak of graph scatter.

4.3. Properties of Concrete.

Concrete properties were investigated in its fresh and hardened state. Fresh properties slump test was used to determine the desired workability. Whereas, hardened properties were obtained to determine the performance of concrete under different course of action.

4.3.1. Properties of Fresh Concrete using Slump Test

The properties of fresh concrete were measured based on its workability characteristics. Superplasticizer or also known as high water reducing admixture was used and was added into the concrete mix proportion to get the desired workability of 60 ± 10mm. The control mix was made of 0.5 w/c ratio, which was kept constant in other mixes. Measured slump for all concrete mixes is given in Table 4.4 and 4.5.

Table 4.4 Measured Slump of Concrete (Designed graded aggregate)

Mix Series ('Designed')	OPC (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	W/C Ratio	SF (%)	SP (%)	Slump (mm)
250CM	250	860	1290	0.5	0	3	52
250SF5	250	860	1290	0.5	5	3	58
250SF10	250	860	1290	0.5	10	3	64
275CM	275	850	1275	0.5	0	3	53
275SF5	275	850	1275	0.5	5	3	60
275SF10	275	850	1275	0.5	10	3	66
350CM	350	840	1260	0.5	0	3	55
350SF5	350	840	1260	0.5	5	3	62
350SF10	350	840	1260	0.5	10	3	67
400CM	400	830	1245	0.5	0	3	58
400SF5	400	830	1245	0.5	5	3	66
400SF10	400	830	1245	0.5	10	3	69

Table 4.5 Measured Slump of Concrete (As-supplied aggregates)

Mix Series ('As-supplied')	OPC (kg/m³)	FA (kg/m³)	CA (kg/m³)	W/C Ratio	SF (%)	SP (%)	Slump (mm)
250CM	250	860	1290	0.5	0	3	50
250SF5	250	860	1290	0.5	5	3	54
250SF10	250	860	1290	0.5	10	3	58
275CM	275	850	1275	0.5	0	3	52
275SF5	275	850	1275	0.5	5	3	57
275SF10	275	850	1275	0.5	10	3	61
350CM	350	840	1260	0.5	0	3	54
350SF5	350	840	1260	0.5	5	3	58
350SF10	350	840	1260	0.5	10	3	63
400CM	400	830	1245	0.5	0	3	56
400SF5	400	830	1245	0.5	5	3	63
400SF10	400	830	1245	0.5	10	3	66

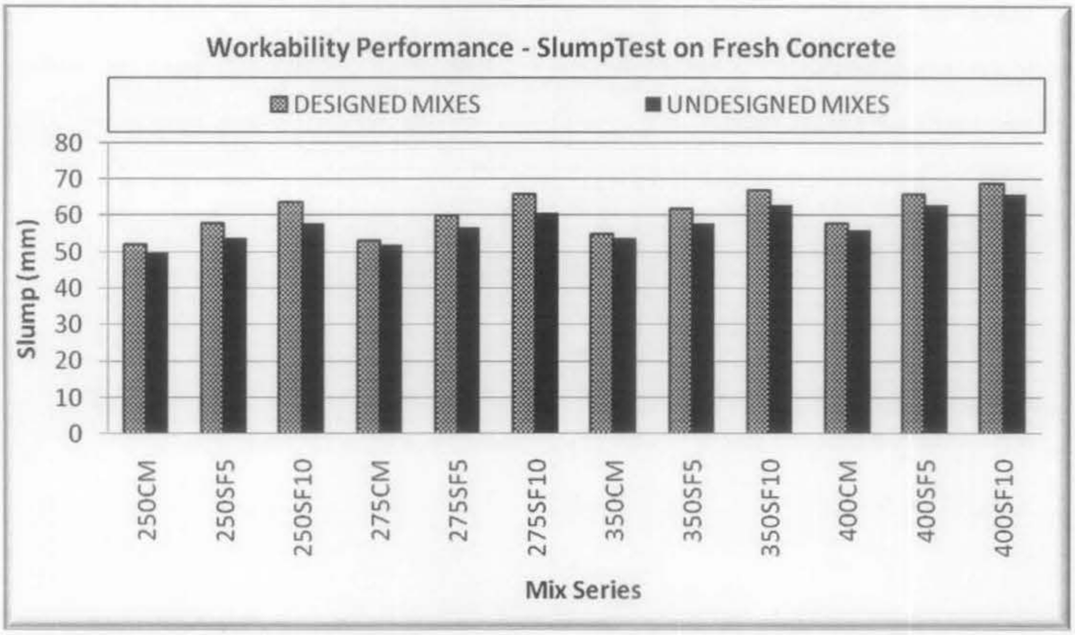


Figure 4.6 Workability Performances – Slump Test on Fresh Concrete

From Figure 4.6, the addition of SF into the concrete mixture has increased the concrete workability. Besides that, the increased amount of OPC used in mix series has also increased the workability of the concrete. This was mainly due to the segregation in aggregates caused by uneven size distribution in the 'As-supplied' mixes. The absorptive characteristic of SF cellular particles, thus concrete which contains higher amount of SF has greater ability to absorb water where it has reduced the tendency of bleeding. Thus the 'As-supplied' mixes required more water to achieve the required stability and workability. This has weakened the concrete's performance in terms of strength performance and durability.

However for results obtained from 'Designed' mixes, the workability of the concrete is higher and better than the 'As-supplied' mixes. The amount of OPC has also increased the workability of the concrete mix. This has indirectly proved that good aggregate gradings contributed to the high workability performance of the concrete. OPC is not the only main consideration in improving concrete's workability and strength.

The slump for this research was controlled within the range of 50 mm – 70 mm in HPC (Silica Fume Association, 2008). The designed slump was purposed to evaluate the workability of the concrete in terms of the effects of aggregates distribution and the addition effects of OPC and SF. As proven the workability of 'Designed' mixes was better than the 'As-supplied' mixes. 'Designed' mixes required less water during mixing and achieved ideal slump values.

4.3.2. Hardened Concrete Properties

4.3.2.1 Compressive Strength Test

The test was conducted to analyze the impact of OPC and SF addition into the concrete mix proportion. The results were arranged in Table 4.6 ('Designed' mixes) and Table 4.7 ('As-supplied' mixes);

Table 4.6 Compressive Strength Developments – 'Designed' Mixes

Mix Series ('Designed')	Age (Days)			
	3	7	28	120
	Compressive Strength (MPa)			
250CM	14.65	18.22	62.07	77.01
250SF5	38.18	43.12	62.20	78.95
250SF10	37.13	43.62	62.30	79.15
275CM	19.10	40.14	62.42	72.59
275SF5	46.70	50.50	68.42	85.40
275SF10	46.75	51.08	63.70	92.70
350CM	22.30	43.44	64.57	80.50
350SF5	41.83	49.67	67.50	102.30
350SF10	50.95	55.33	70.70	113.34
400CM	26.67	44.98	63.28	89.67
400SF5	45.55	49.95	69.34	117.21
400SF10	55.48	60.72	85.95	136.80

Table 4.7 Compressive Strength Developments – 'As-supplied' Mixes

Mix Series ('As-supplied')	Age (Days)			
	3	7	28	120
	Compressive Strength (MPa)			
250CM	9.65	12.21	42.26	57.20
250SF5	27.18	33.42	52.40	70.59
250SF10	30.13	40.21	58.65	72.65
275CM	12.23	36.91	53.24	59.65
275SF5	32.80	45.28	60.23	74.20
275SF10	35.89	48.82	62.95	83.91
350CM	20.21	38.54	59.75	65.50
350SF5	32.95	46.31	65.33	88.37
350SF10	35.92	50.35	66.32	105.64
400CM	22.58	40.13	63.28	72.54
400SF5	33.81	48.90	69.34	98.21
400SF10	42.95	52.27	85.95	128.46

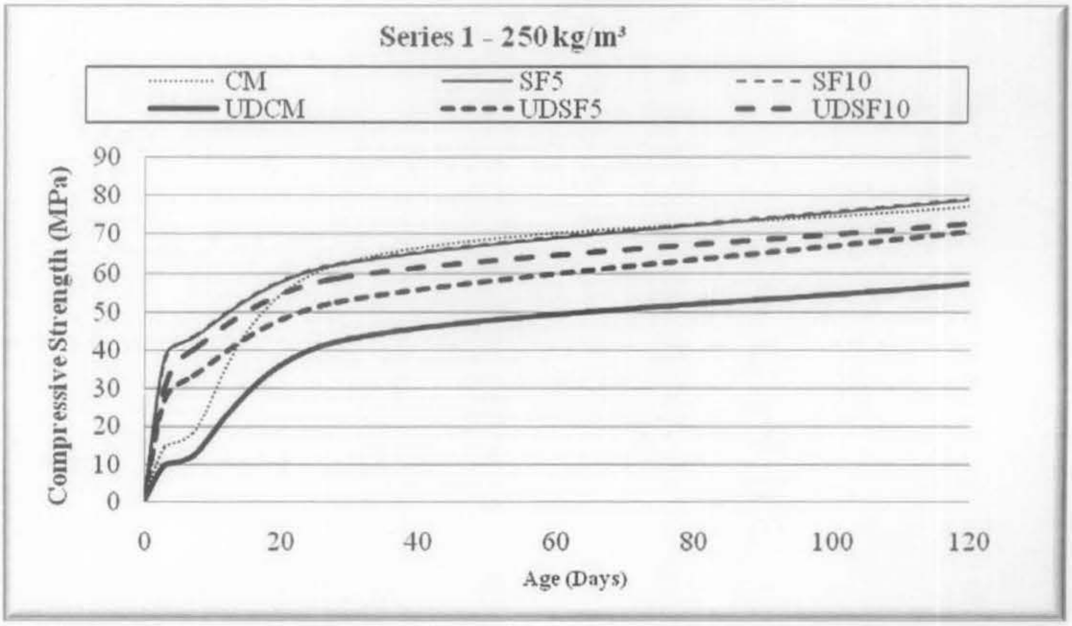


Figure 4.7 Compressive Strength Development of Series 1 (250 kg/m^3)

From Figure 4.7, at the age of 28 days, the compressive strengths achieved between the 'Designed' and 'As-supplied' mixes for the control mixes (CM) with 100% OPC was 10%, addition of 5% SF (SF5) was 5% and addition of 10% SF (SF10) was 8% . The compressive strength changed after 28 days age and were higher compared to the 3 days age which was 2% for CM, 16% for SF5 and 10% for SF10. From CM, SF5 compressive strength had increased by 5% while SF10 by 12%.

At the age of 120 days, compressive strength has further increased. In CM mixes, the compressive strength has increased within the range of 10% to 30% when SF was added. The increment was not obvious and was to be almost stagnant. However, when SF was added, the strength changes were obvious. If compared to compressive strength obtained in CM, compressive strength in SF5 has increased by 10% while SF10 has increased by 60%.

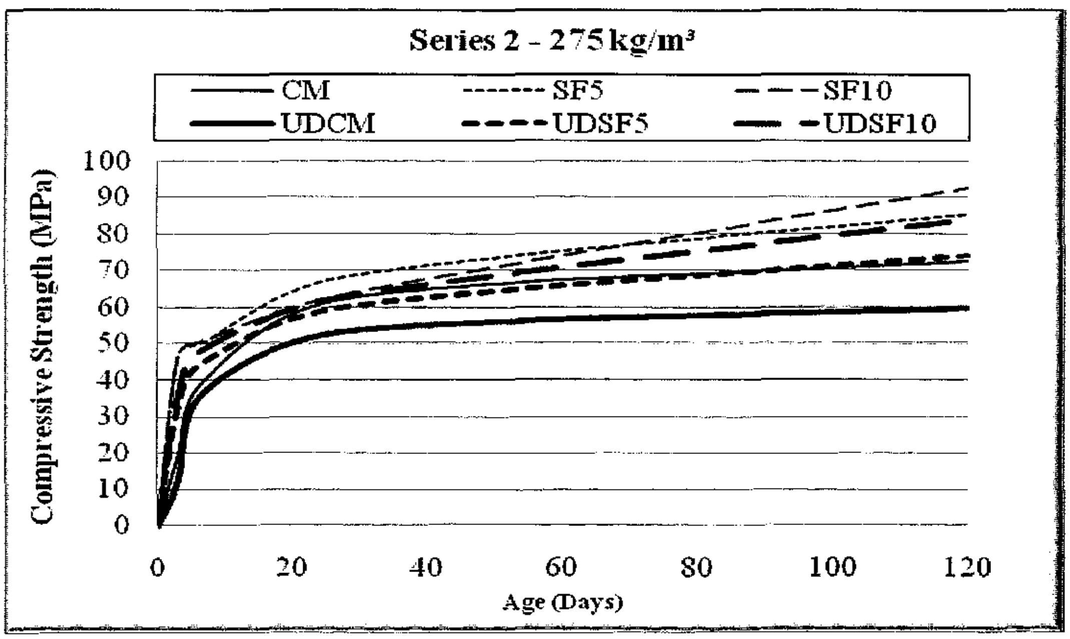


Figure 4.8 Compressive Strength Development of Series 2 (275 kg/m³)

From Figure 4.8, at the age of 28 days, the compressive strengths achieved between the 'Designed' and 'As-supplied' mixes for the control mixes (CM) with 100% OPC was 15%, addition of 5% SF (SF5) was 30% and addition of 10% SF (SF10) was 8% .

The compressive strength changed and was higher compared to the 3 days age that was 15% for CM, 20% for SF5 and 12% for SF10. With addition of 5% SF, the compressive strength increased 10% from CM and with the addition of 10% SF, the compressive strength has further increased by 20%.

At the age of 120 days, compressive strength has increased. However in CM mixes, the compressive strength has increased within the range of 10% to 30% when SF was added. However, when SF was added, the strength changes were obvious. If compared to compressive strength obtained in CM, with addition of 5% SF, compressive strength has increased by 20% while with 10% SF added, compressive strength has increased by 70%.

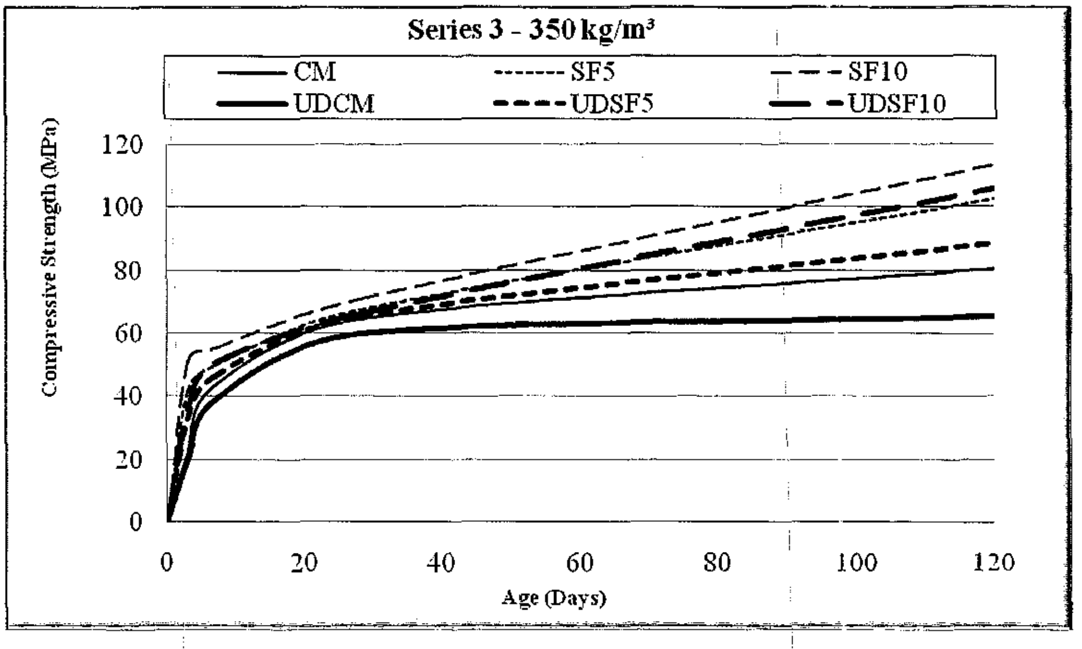


Figure 4.9 Compressive Strength Development of Series 3 (350 kg/m³)

From Figure 4.9, at the age of 28 days, the compressive strengths achieved between the 'Designed' and 'As-supplied' mixes for the control mixes (CM) with 100% OPC was 20%, addition of 5% SF (SF5) was 14% and addition of 10% SF (SF10) was 10% . The compressive strength changed and was higher compared to the 3 days age that was 10% for CM, 5% for SF5 and 10% for SF10. With addition of 5% SF, the compressive strength increased 5% from CM and with the addition of 10% SF, the compressive strength has further increased by 15%.

At the age of 120 days, compressive strength has increased. However in CM mixes, the compressive strength has increased 15% when SF was added. The strength changes were obvious. If compared to compressive strength obtained in CM, with SF5, compressive strength has increased by 15% while with SF10, compressive strength has increased by 45%.

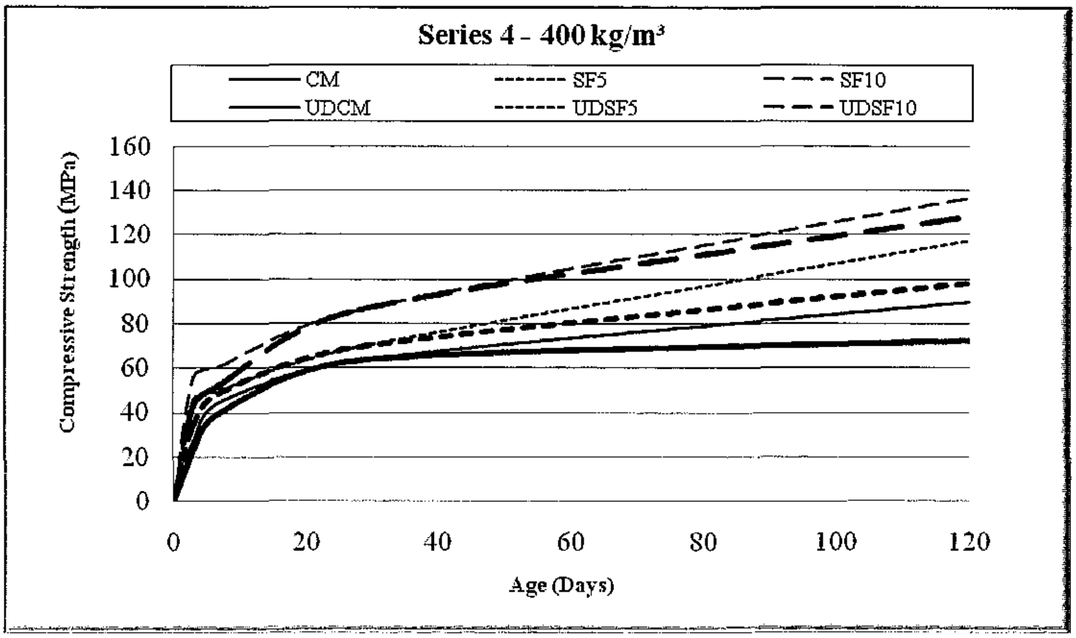


Figure 4.10 Compressive Strength Development of Series 4 (400 kg/m^3)

From Figure 4.10, at the age of 28 days, the compressive strengths achieved between the 'Designed' and 'As-supplied' mixes for the control mixes (CM) with 100% OPC was 20%, addition of 5% SF (SF5) was 16% and addition of 12% SF (SF10) was 10% . The compressive strength changed and was higher compared to the 3 days age that was 5% for CM, 3% for SF5 and 20% for SF10. With addition of 5% SF, the compressive strength increased 10% from CM and with the addition of 10% SF, the compressive strength has further increased by 30%.

At the age of 120 days, compressive strength has increased. However in CM mixes, the compressive strength has increased 15% when SF was added. The strength changes were obvious. If compared to compressive strength obtained in CM, with SF5, compressive strength has increased by 15% while with SF10, compressive strength has increased by 50%.

As proven by T.W. Bremner (1997), the impact of aggregate segregation and distribution in concrete affects the compressive strength development of concrete. This resulted that well graded and finely distributed aggregates in concrete has contributed to the high compressive strength of concrete. SF has proved to be an ideal cement replacing material (CRM). SF has contributed greatly in the high strength development of the concrete. With the small amount of cement used in mix proportion, high strength was achieved thus OPC was not the main consideration to obtain high strength in concrete.

'Designed' mixes has the characteristics of being well compact, solid and no segregation. Fine pores or micro-cracks were filled with aggregates and with the addition of silica fume (SF), reduces bleeding in concrete. The addition of SF in each mix series has also contributed to the high strength obtained at the 28 days age as much as 20%. Thus in terms of performance, cement content is not the main consideration to obtain high strength in concrete. With reduced cement content in concrete mixes, high strength in performance can still be obtained. Thus the ideal mix design was Series 1 of the 'Designed' mixes.

4.3.2.2 High Early Compressive Strength Analyses.

The early compressive strength was analyzed to determine the impact of SF addition into the concrete mix series. The strength developments of concrete samples were measured at 3 and 7 days of age for both 'Designed' and 'As-supplied' concrete mixes. The data obtained were arranged in Table 4.8 ('Designed' Mixes) and Table 4.9 ('As-supplied' Mixes) as shown;

Table 4.8: Early Compressive Strength for 'Designed' Mixes

Mix Series ('Designed')	Age (Days)	
	3	7
	Compressive Strength (MPa)	
250CM	14.65	18.22
250SF5	38.18	43.12
250SF10	37.13	43.62
275CM	19.10	40.14
275SF5	46.70	50.50
275SF10	46.75	51.08
350CM	22.30	43.44
350SF5	41.83	49.67
350SF10	50.95	55.33
400CM	26.67	44.98
400SF5	45.55	49.95
400SF10	55.48	60.72

Table 4.9 Early Compressive Strength for 'As-supplied' Mixes

Mix Series ('As-supplied')	Age (Days)	
	3	7
	Compressive Strength (MPa)	
250CM	9.65	12.21
250SF5	27.18	33.42
250SF10	30.13	40.21
275CM	12.23	36.91
275SF5	32.80	45.28
275SF10	35.89	48.82
350CM	20.21	38.54
350SF5	32.95	46.31
350SF10	35.92	50.35
400CM	22.58	40.13
400SF5	33.81	48.90
400SF10	42.95	52.27

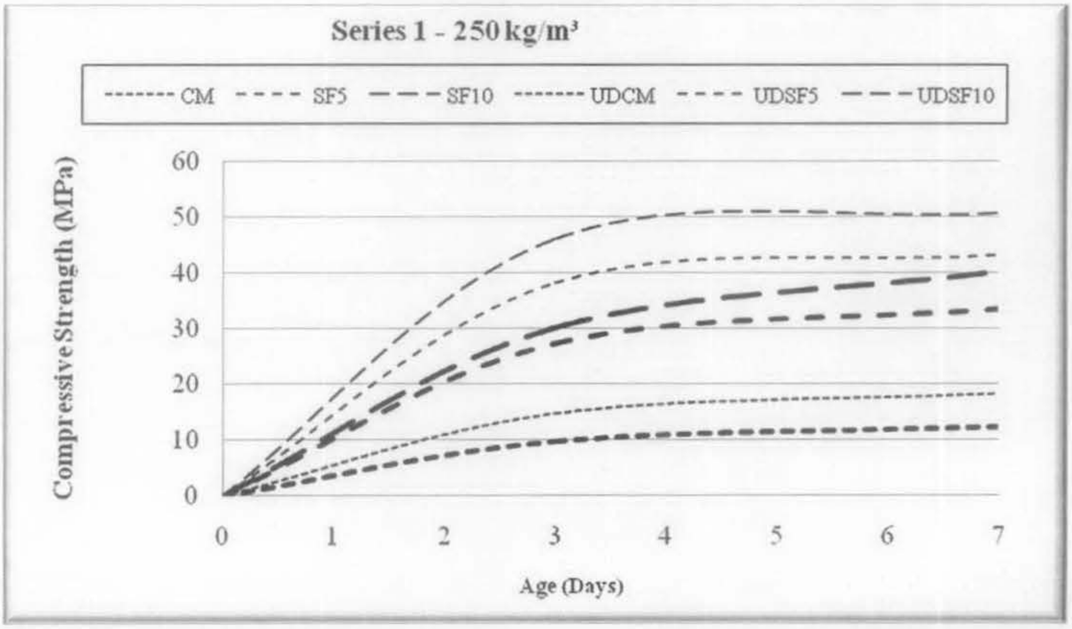


Figure 4.11 High Early Compressive Strength – Series 1 (250 kg/m³)

From Figure 4.11, at the 3 days age, there were increment in compressive strengths between the 'Designed' and 'As-supplied' mixes. For CM, the strength increased 40%, SF5 with 33% and SF10 with 40%. At 7 days age, with the addition of SF, compressive strength has greatly increased by 60% in SF5 and 70% in SF10

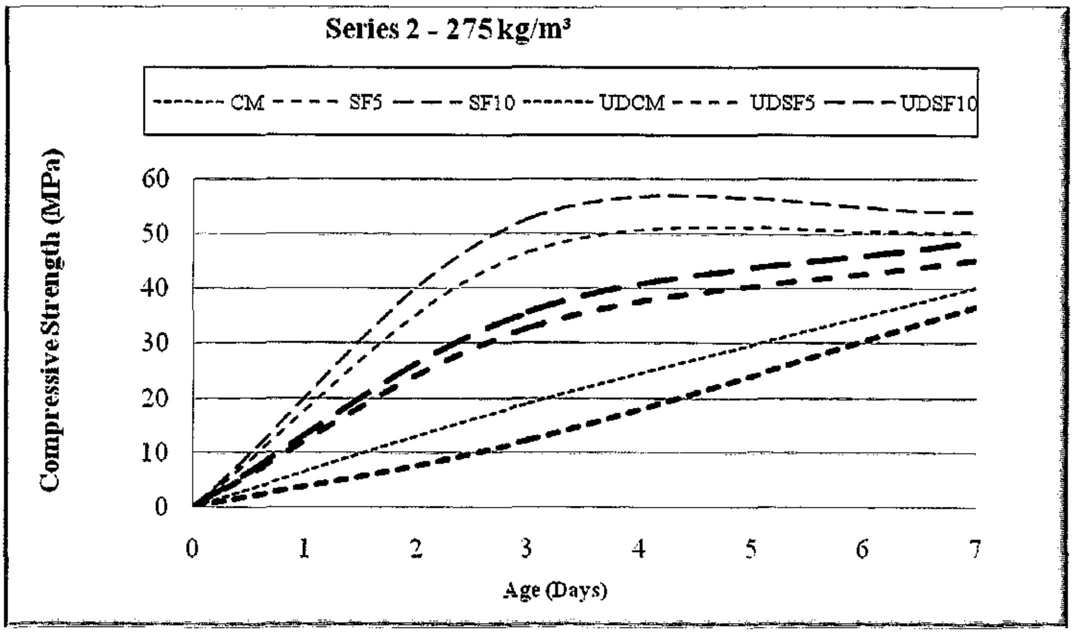


Figure 4.12 High Early Compressive Strength – Series 2 (275 kg/m³)

From Figure 4.12, at the 3 days age, there were increment in compressive strengths between the 'Designed' and 'As-supplied' mixes. For CM, the strength increased 40%, SF5 with 36% and SF10 with 40%. At 7 days age, with the addition of SF, compressive strength has greatly increased by 62% in SF5 and 70% in SF10

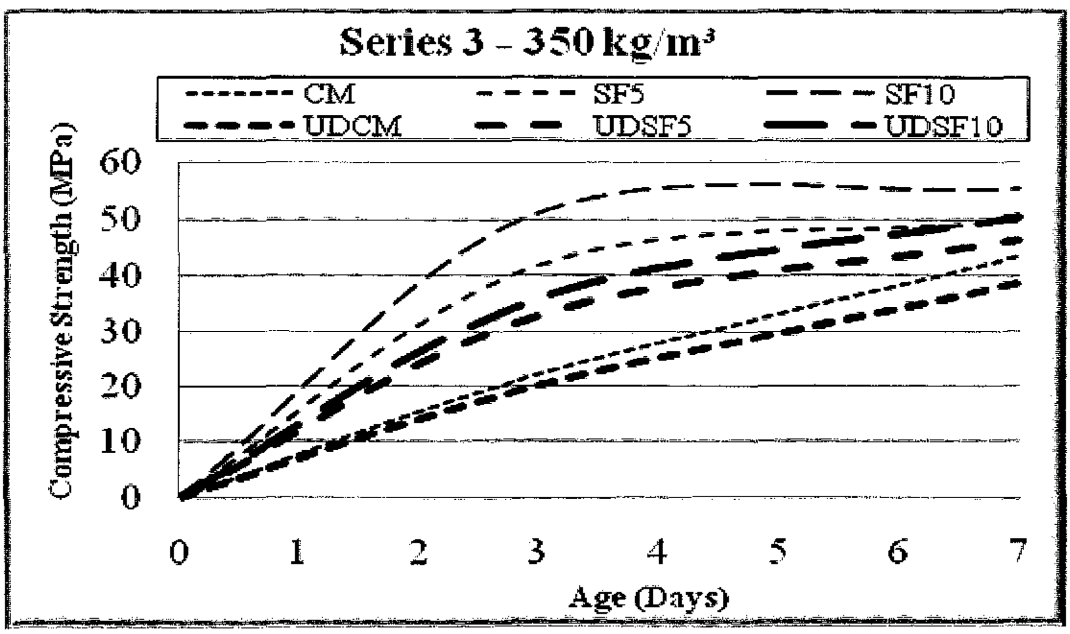


Figure 4.13 High Early Compressive Strength – Series 3 (350 kg/m³)

From Figure 4.13, at the 3 days age, there were increment in compressive strengths between the 'Designed' and 'As-supplied' mixes. For CM, the strength increased 34%, SF5 with 40% and SF10 with 42%. At 7 days age, with the addition of SF, compressive strength has greatly increased by 50% in SF5 and 70% in SF10.

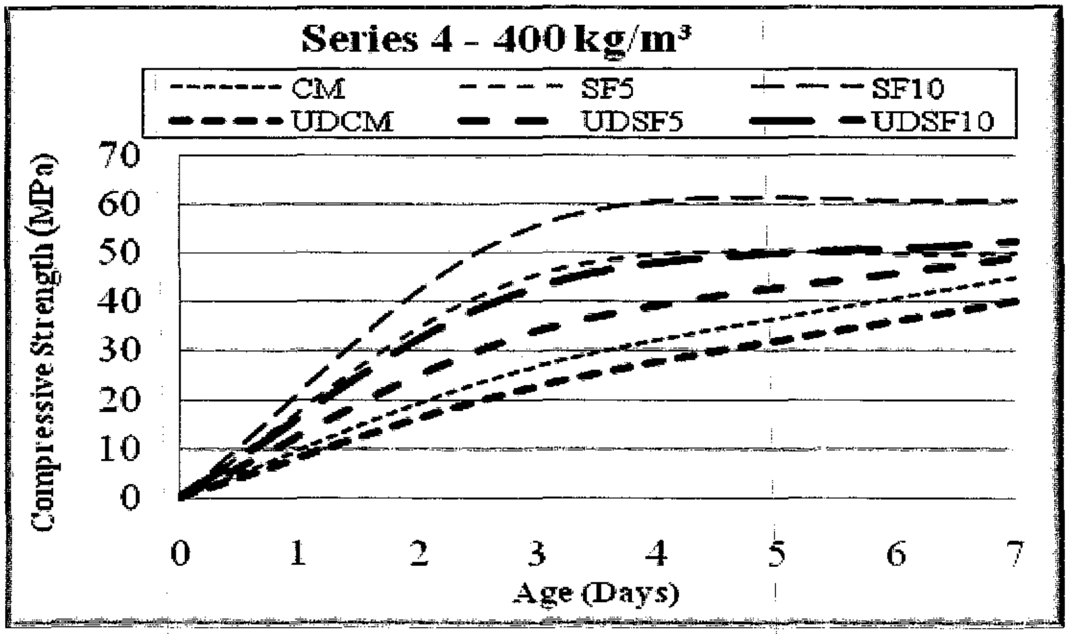


Figure 4.14 High Early Compressive Strength – Series 4 (400 kg/m³)

From Figure 4.14, at the 3 days age, there were increment in compressive strengths between the 'Designed' and 'As-supplied' mixes. For CM, the strength increased 33%, SF5 with 40% and SF10 with 40%. At 7 days age, with the addition of SF, compressive strength has greatly increased by 43% in SF5 and 60% in SF10.

Overall, as observed from the figures, the early compressive strength obtained from 'Designed' mixes were higher than 'As-supplied' mixes as much as 5% - 10% in each mix series. The strength values obtained from CM in each mix series were high which is around 20 MPa and is suitable for land constructions. The addition of SF has enhanced the concrete's performance in high early strength development and was ideal for marine structures constructions where the strength value obtained from this research was more than 40 MPa. SF has contributed greatly to the increase of high early strength in concrete.

As can be observed from the figures, compressive strength of SF5 and SF10 obtained were more than 40 MPa. The compressive strength results obtained were higher than minimum 35 MPa. SF being an ideal CRM is not a myth but a great CRM. 10% of SF added contributes to 30% of strength increase as it forms a surface coating on cement particles increasing the chemical reactions among particles with improved interfacial layer (bond) (K. Day, 1993). With the application of well graded and finely distributed aggregates as produced from 'Designed' mixes, an improved concrete material has developed.

This was so, as mixes will be more workable, compact, solid, reduced in material size as less formwork will be used but with maintained high strength or higher strength, reduces cost and maximizes profits of parties involved. Such high strength of 40 MPa, is high in demand by contractors and developers for fast pace constructions in this modern urbanization. Thus the ideal mix design was Series 1 of the 'Designed' mixes.

4.3.2.3 Porosity Test

The porosity test was conducted to determine the impact of OPC and SF addition into the concrete mix series. The porosity (%) of concrete samples were measured at 3, 7, 28, 56 and 120 days of age for both 'Designed' and 'As-supplied' concrete mixes. The data obtained were arranged in Table 4.10 ('Designed' Mixes) and Table 4.11 ('As-supplied' Mixes).

Table 4.10 Porosity for 'Designed' Mixes

Mix Series ('Designed')	Age (Days)				
	3	7	28	56	120
	Porosity (%)				
250CM	8.34	6.03	4.01	3.22	3.17
250SF5	8.32	6.75	4.00	3.08	1.89
250SF10	8.23	6.80	4.00	3.20	2.92
275CM	4.51	4.37	3.08	2.52	1.10
275SF5	6.91	4.08	3.82	3.05	2.69
275SF10	6.59	6.44	4.02	3.13	2.24
350CM	7.11	5.85	5.37	4.72	4.61
350SF5	6.84	5.05	4.15	3.53	2.62
350SF10	7.28	6.80	4.81	3.10	1.07
400CM	6.89	6.37	4.93	3.89	2.25
400SF5	6.35	6.27	5.67	5.28	3.60
400SF10	6.20	6.12	5.05	4.04	2.01

Table 4.11 Porosity for 'As-supplied' Mixes

Mix Series ('As-supplied')	Age (Days)				
	3	7	28	56	120
	Porosity (%)				
250CM	8.80	6.34	4.21	3.40	3.33
250SF5	9.20	7.43	4.40	3.76	2.08
250SF10	9.06	7.50	4.76	3.52	3.22
275CM	6.77	6.56	4.62	3.80	1.70
275SF5	10.37	6.12	5.73	4.60	4.04
275SF10	9.90	8.40	5.23	4.07	2.92
350CM	9.24	7.61	7.00	6.14	6.00
350SF5	8.90	6.57	5.40	4.60	3.41
350SF10	9.50	8.84	6.26	4.03	1.40
400CM	10.34	9.56	7.40	5.84	3.38
400SF5	9.53	9.41	8.51	7.92	5.40
400SF10	9.30	9.20	7.60	6.06	3.02

From Figure 4.15, 4.16, 4.17 and 4.18, the porosity values in each mix series reduced with age. From Figure 4.15, at the 3 days age, the porosity of 'Designed' mixes has reduced 27% while 'Undesigned' mixes has reduced 25% with a difference of 2%. Gradual decrease of values occurred as much as 2% in every age day. However as cement consumption in mix series for 'Designed' mixes increases significant decrease as much as 50% - 70% in porosity values compared to 'As-supplied' mixes were observed from Figure 4.16, 4.17 and 4.18.

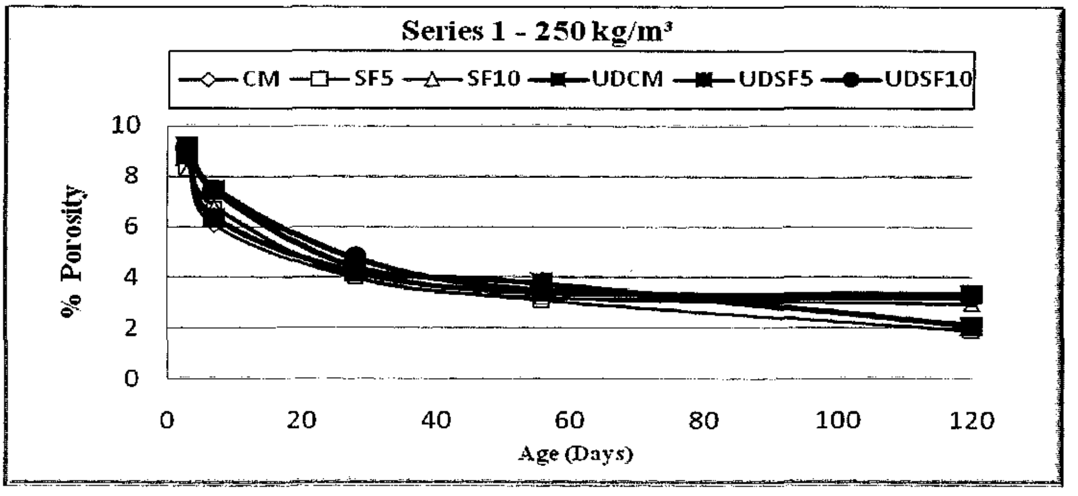


Figure 4.15 Total Porosity Development – Series 1 (250 kg/m^3)

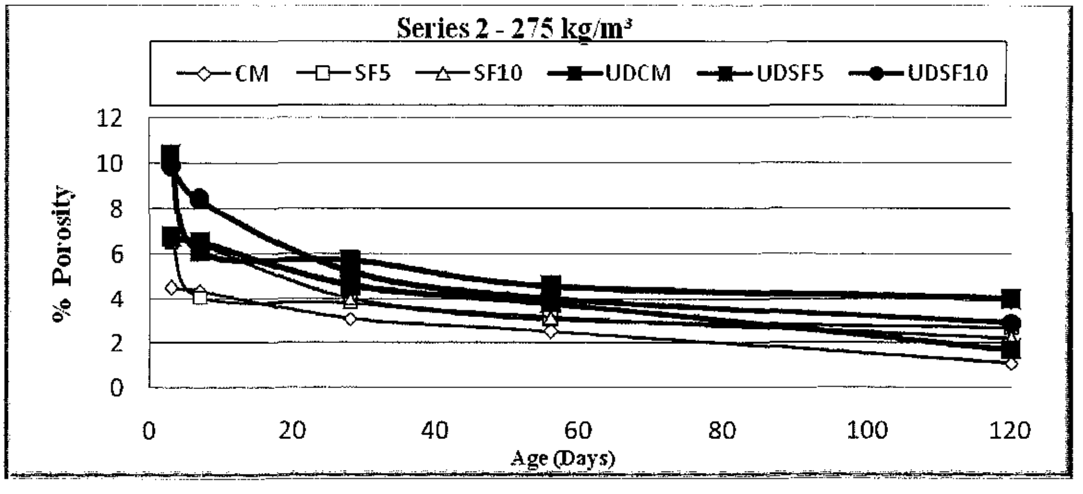


Figure 4.16 Total Porosity Development – Series 2 (275 kg/m^3)

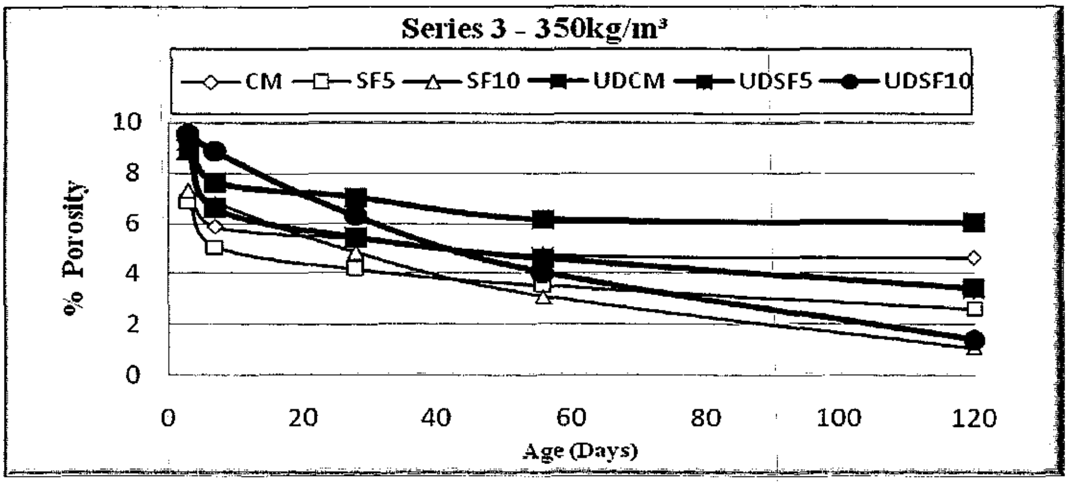


Figure 4.17 Total Porosity Development – Series 3 (350 kg/m³)

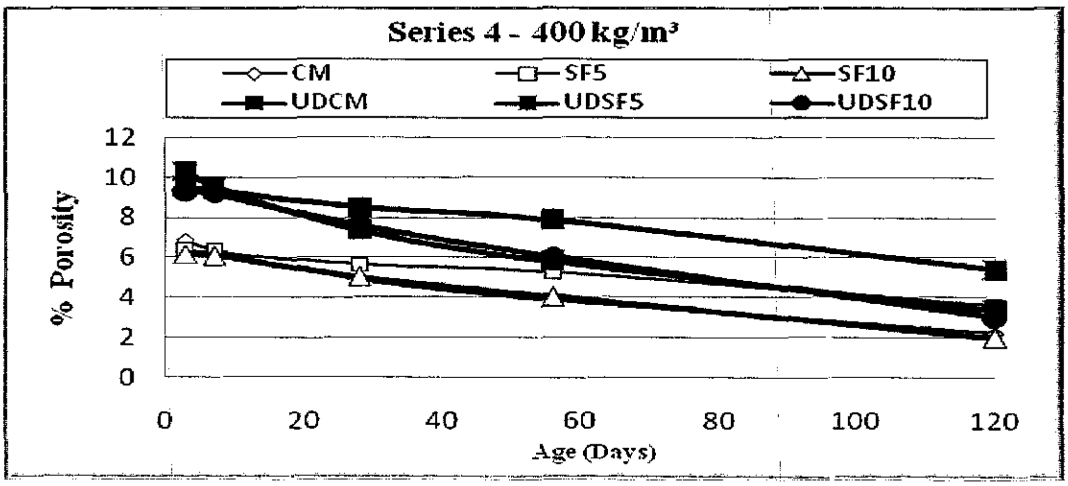


Figure 4.18 Total Porosity Development – Series 4 (400 kg/m³)

Low percentage values in porosity are good as it shows that the concrete is durable, solid and compact. It can be determined that no segregation of aggregates in concrete during mixing process. From this research, the impact of OPC and SF can be determined in detail. Based on results analysis, it is determined that 'Designed' mixes performed better than 'As-supplied' mixes. With the addition of SF, the qualities of the concrete mixes produced were further enhanced.

The addition of SF into concrete mixes caused big reductions in porosity values as much as 3%-4% in every age day in each mix series. SF has filled the pores that was inside the concrete directly reduces bleeding effects. SF also has very small particle size, 1μm. It takes about 6 000,000 particles to form a particle of OPC (SFA, 1997).

Based on discussions, the decrease in total porosity was observed during the hydration process. Large capillary pore spaces were filled with the hydration products, for this research is SF as CRM during cement hydration. Thus, this refined the size of the pores where it directly increased the cumulative volume of very fine gel pores. Figure 4.19 shows the overall total porosity development in every mix series for both 'Designed' and 'As-supplied' Mixes.

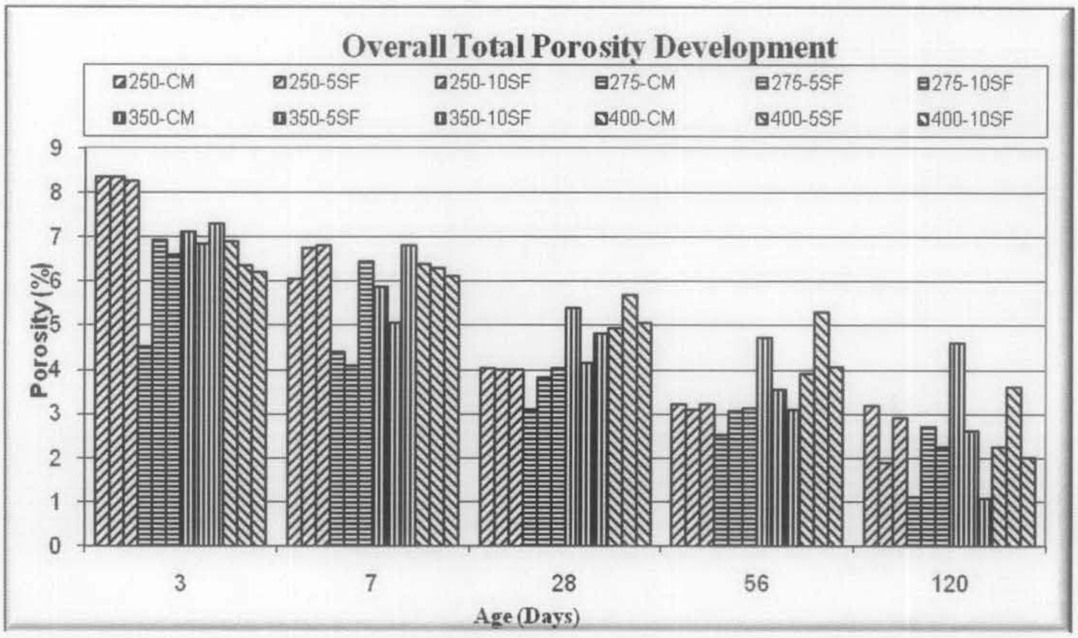


Figure 4.19: Overall Porosity Development-'Designed' and 'As-supplied' Mixes

The overall total porosity developments in both mixes were ideal. Percentage of porosity reduced with age. Reduced cement content has managed to maintain high strength with low porosity adding durability benefits to the concrete material. Cement content was not the main consideration to maintain durability of a concrete but well graded and finely distributed aggregates also played the main role in high durability of concrete.

4.3.2.4 Split Cylinder Test

The tensile strength developments (MPa) of concrete samples were obtained at 28 and 90 days of age for both 'Designed' and 'As-supplied' concrete mixes. The datas obtained were arranged in Table 4.12 ('Designed' Mixes) and Table 4.13 ('As-supplied' Mixes).

Table 4.12: Split Tensile Strength Development (MPa) – Designed Mixes

Mix Series ('Designed')	Age (Days) 28	120
	Tensile Strength (MPa)	
250CM	3.250	3.363
250SF5	3.180	3.260
250SF10	2.207	2.932
275CM	2.892	3.304
275SF5	3.675	4.625
275SF10	3.677	4.706
350CM	2.853	3.256
350SF5	3.530	4.177
350SF10	4.756	4.981
400CM	3.220	3.586
400SF5	3.478	4.387
400SF10	4.698	4.894

Table 4.13: Split Tensile Strength Development (MPa) – 'As-supplied' Mixes

Mix Series ('As-supplied')	Age (Days) 28	120
	Tensile Strength (MPa)	
250CM	2.600	2.700
250SF5	2.540	2.610
250SF10	1.770	2.350
275CM	2.320	2.640
275SF5	2.940	3.700
275SF10	3.120	3.850
350CM	2.300	2.610
350SF5	2.820	3.360
350SF10	3.840	4.040
400CM	2.580	2.900
400SF5	2.780	3.600
400SF10	3.800	3.920

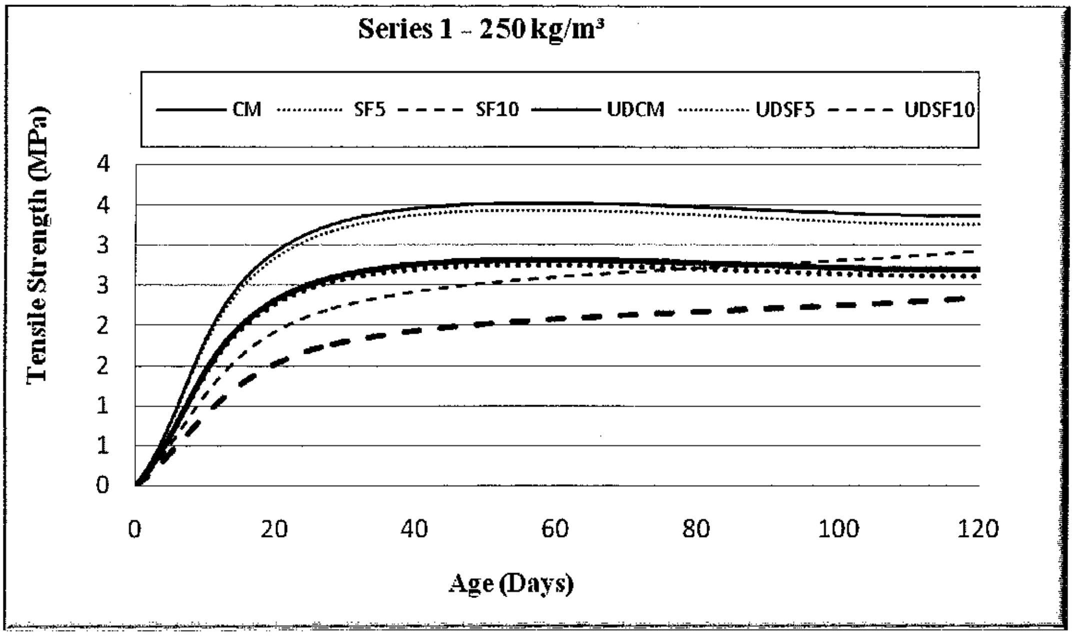


Figure 4.20: Split Tensile Strength Development (MPa) – Series 1 (250 kg/m³)

From Figure 4.20, at 28 days age, the tensile strength has increased in both mixes. In CM, the tensile strength has increased 20%, SF5 with 30% and SF10 with 40%. At 90 days, the tensile strength increased 20% in CM, 40% in SF5 and 52% in SF10.

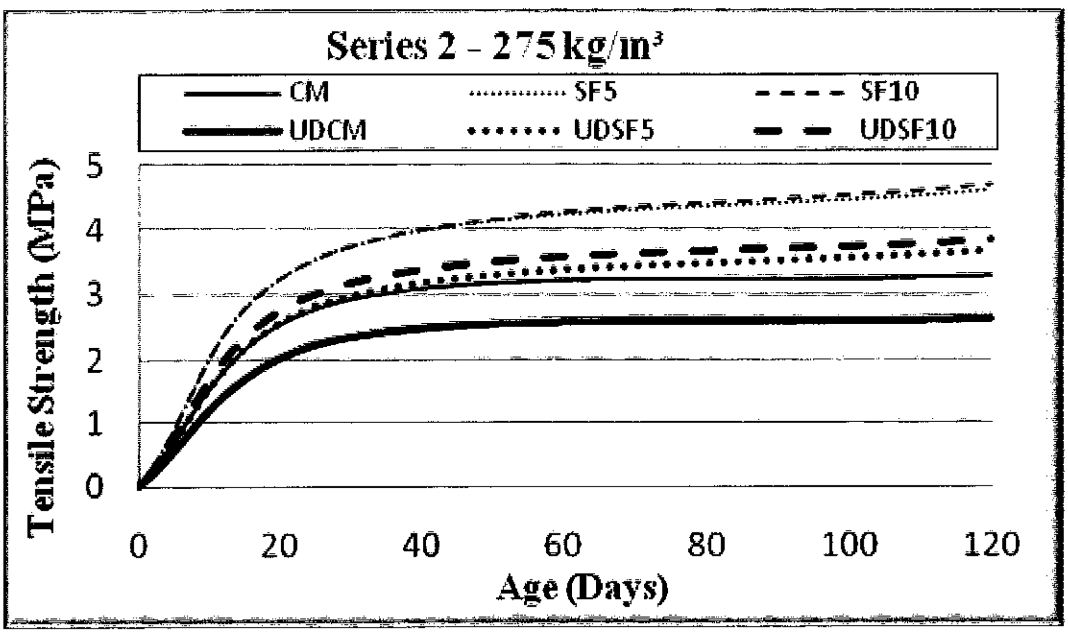


Figure 4.21: Split Tensile Strength Development (MPa) – Series 2 (275 kg/m³)

From Figure 4.21, at 28 days age, the tensile strength has increased in both mixes. In CM, the tensile strength has increased 20%, SF5 with 35% and SF10 with 45%. At 90 days, the tensile strength increased 30% in CM, 45% in SF5 and 60% in SF10.

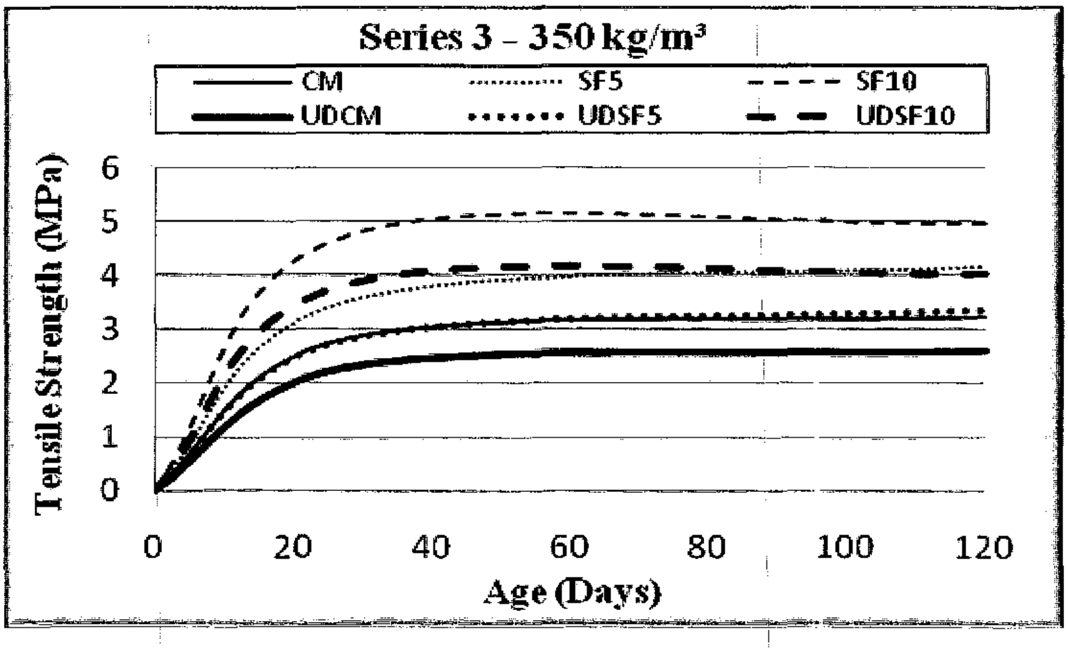


Figure 4.22: Split Tensile Strength Development (MPa) – Series 3 (350 kg/m³)

From Figure 4.22, at 28 days age, the tensile strength has increased in both mixes. In CM, the tensile strength has increased 20%, SF5 with 30% and SF10 with 40%. At 90 days, the tensile strength increased 20% in CM, 50% in SF5 and 62% in SF10.

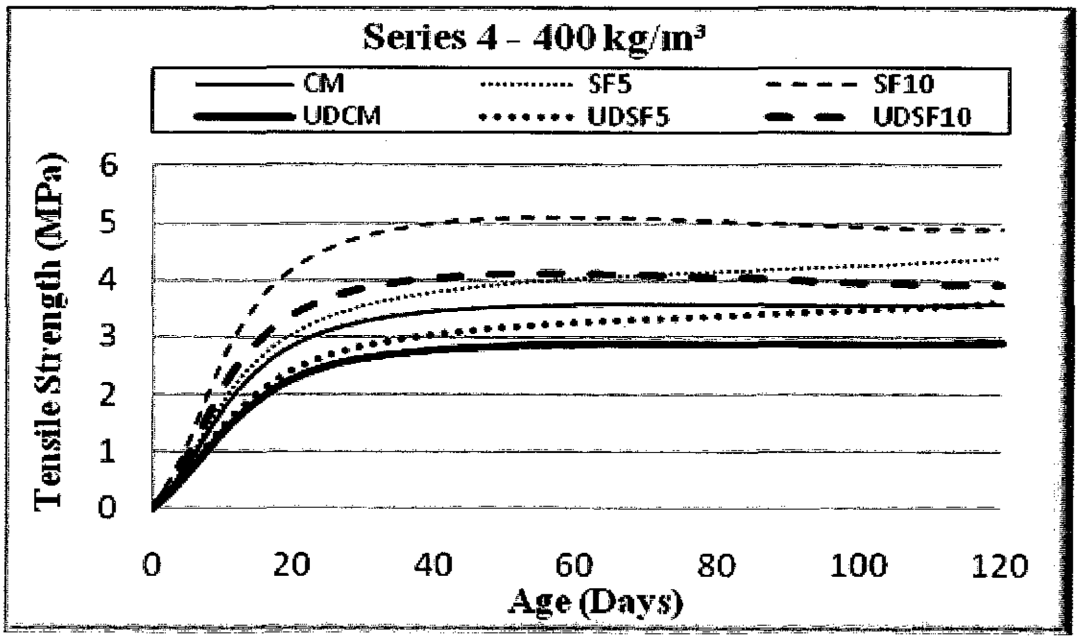


Figure 4.23: Split Tensile Strength Development (MPa) – Series 4 (400 kg/m³)

From Figure 4.23, at 28 days age, the tensile strength has increased in both mixes. In CM, the tensile strength has increased 20%, SF5 with 30% and SF10 with 45%. At 90 days, the tensile strength increased 30% in CM, 60% in SF5 and 70% in SF10.

Low tensile strength has values ranging from 1-2 MPa (Nawa and Horita, 2004). Tensile strength values obtained were more than 2 MPa and have a maximum value of 5MPa (Table 4.14). Low tensile strength in concrete at 28 days of age brings out great risk of material defects such as cracking.

High tensile strength values contribute to high durability of material characteristics. Tensile strength represents the brittleness of a material and the behaviour of material in sustaining different environment conditions. Although with reduced cement content, high strength was achieved. SF was an ideal CRM. Thus, Series 1 of the 'Designed' mixes was the ideal mix design with high tensile values.

4.3.2.5 Chloride Migration Test

The chloride penetration results of concrete samples were obtained at 28, 120 and 180 days of age for both 'Designed' and 'As-supplied' concrete mixes. The results obtained were arranged in Table 4.14 ('Designed' Mixes) and Table 4.15 ('As-supplied' Mixes).

Table 4.14: Chloride Penetration – 'Designed' Mixes

Mix Series ('Designed')	Age (Days)		
	28	120	180
	Chloride Penetration Depth (mm)		
250CM	2.94	5.24	6.15
250SF5	1.53	2.72	4.93
250SF10	1.37	2.61	4.13
275CM	1.35	2.87	5.19
275SF5	1.25	2.24	4.06
275SF10	1.19	2.12	3.90
350CM	2.83	3.54	4.27
350SF5	2.21	3.44	3.88
350SF10	2.08	3.35	3.49
400CM	2.00	2.56	3.15
400SF5	1.88	2.39	2.82
400SF10	1.84	2.24	2.73

From Table 4.16, at the 28 days age, the chloride penetration depth decreased in every mix series with the addition of SF into the sample mixes. SF has micro-filler effects that filled the pores of the concrete. The capillary and pore networks are somewhat disconnected due to the development of self-desiccation (P.C. Aitcin, 2003). As the concrete developed from 28 days age to 180 days age, the penetration depth increased between 5% to 20%. Low penetration values obtained proved that concrete produced from mix designs were durable in the marine environment.

The mechanical properties of concrete were highly dependent on the properties and proportions of aggregates (T. Fuminori and M. Takafumi, 1997). Thus, well graded and finely distributed aggregates contributed to improve durability of concrete. The concrete produced from this mix were compact and solid.

Table 4.15: Chloride Penetration Development – 'As-supplied' Mixes

Mix Series ('As-supplied')	Age (Days)		
	28	120	180
	Chloride Penetration Depth (mm)		
250CM	3.82	6.82	8.05
250SF5	2.15	3.53	6.50
250SF10	1.87	3.46	5.37
275CM	1.76	3.73	6.74
275SF5	1.63	2.91	5.28
275SF10	1.57	2.76	5.07
350CM	3.68	4.61	5.56
350SF5	2.87	4.47	5.04
350SF10	2.70	4.36	4.54
400CM	2.63	3.33	4.10
400SF5	2.45	3.11	3.67
400SF10	2.39	2.92	3.55

From Table 4.17, at the 28 days age, the chloride penetration depth decreased in every mix series with the addition of SF into the sample mixes. SF has helped by having micro-filler effects that filled the pores of the concrete. However, the penetration depth in this mix design was higher compared to the 'Designed' mixes with difference as much as 5%. As the concrete developed from 28 days age to 180 days age, the penetration depth increased as much as 70%. High penetration depth values obtained proved that concrete produced from this mix design especially in CM mix samples in every mix series with maximum depth of 4mm, not very durable in the marine environment.

This was so due to aggregate segregation that occurred in the concrete during hydration. Uneven sizes between aggregates (coarse and fine) were not taken into consideration. Micro-pores existed inside the concrete thus created space for the chloride ions to penetrate further into concrete.

The rate of chloride ion migration into concrete is principally a function of concrete association with chloride ions and concentration of the surrounding salt (Funahashi, 1990). Thus, well graded and finely distributed aggregates should be considered to improve durability of concrete besides increasing the amount of cement consumption.

4.3.2.6. Durability Efficiency.

From Figure 4.24, 180 age day was made 100% chloride penetration efficient. As observed, the durability efficiency increased in 28 and 120 age day. Chloride ion penetration occurred within the mentioned development days but in a very slow rate with maximum increase of 20%. In general, concrete produced from 'Designed' mixes were more efficient compared to the 'As-supplied' mixes.

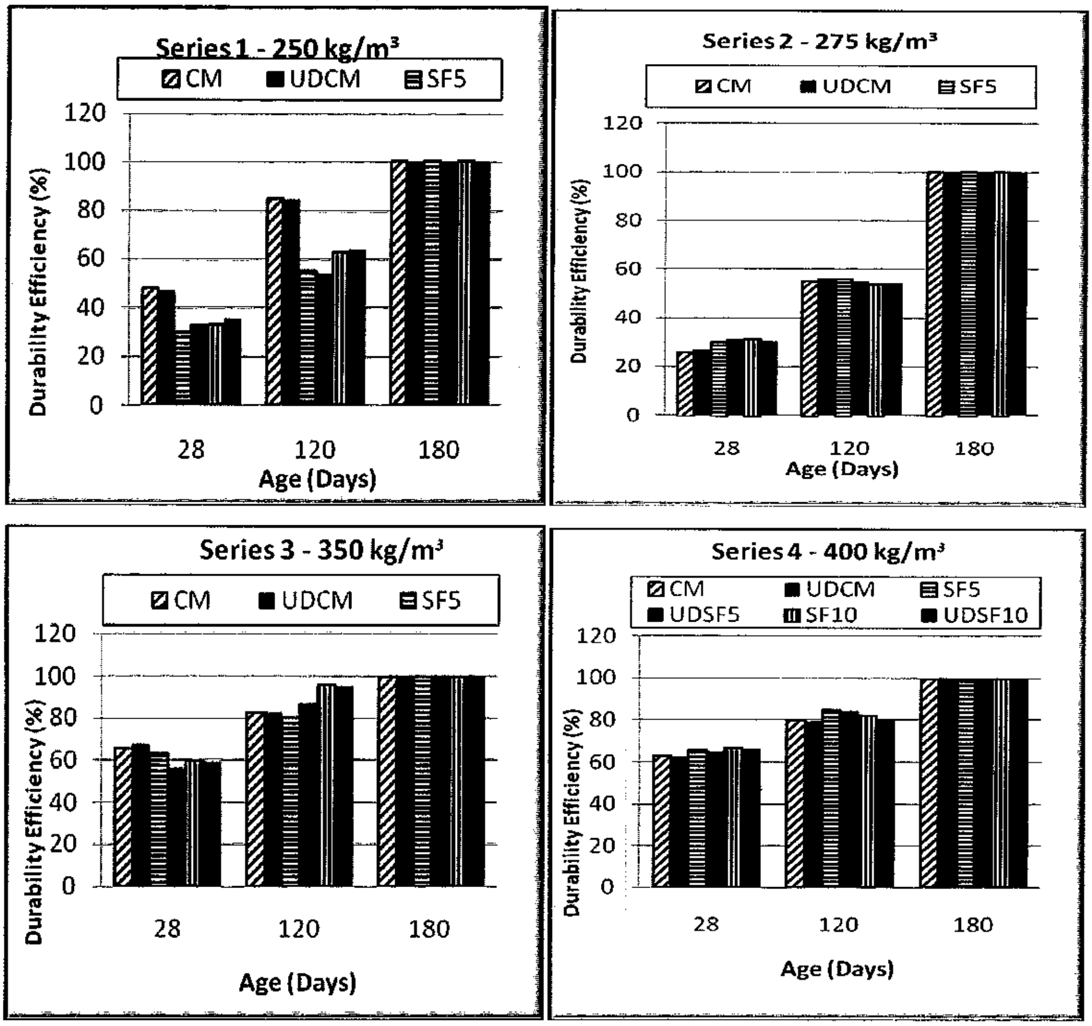


Figure 4.24: Chloride Penetration Efficiency – 'Designed' and 'As-supplied' Mixes.

The addition of SF in sample mixes lead to the process of pore-size and grain-size refinement, which reduces both size and volume of voids, micro-cracks and calcium hydroxide crystals (K.P. Mehta, 1993). The filling space effects of CRMs are as important as pozzolanic effects and for some researchers it can be more important than the pozzolanic effect (A. Goldman, 1992). This proved that concrete produced in this research were durable in the marine environment and able to resists from the attacks of chloride ion salts.

4.3.2.7. Modulus of Elasticity. (Flexural Tensile Strength)

Modulus of Elasticity of concrete is frequently expressed in terms of compressive strength. The mechanical properties of concrete are highly dependent on the properties of aggregates used. It is the key factor to estimate the deformation of buildings and members as well as in designing section of members subjected to flexure (T. Fuminori and M. Takafumi, 1997).

Modulus of Elasticity was described as the stress to strain ratio value for hardened concrete at whatever age and curing condition. The E- Compressive Modulus results were obtained from calculations while the E-Flexural Modulus was taken directly from Universal Testing Machine. The results obtained from were arranged in Table 4.16 ('Designed' Mixes) and Table 4.19 ('As-supplied' Mixes).

Table 4.16: Modulus of Elasticity – 'Designed' Mixes

Mix Series ('Designed')	E - Flexural Modulus (GPa)	E - Compressive Modulus (GPa)
250CM	19.00	20.03
250CM	18.28	22.71
250SF5	17.74	25.12
250SF10	18.97	22.98
275CM	18.91	25.15
275SF5	16.16	27.16
350CM	18.72	22.19
350SF5	18.00	25.56
350SF10	17.14	30.68
400CM	16.67	20.07
400SF5	17.60	26.36
400SF10	18.00	32.24

For the 'Designed' Mixes (E- Flexural Modulus), from Table 4.16, in every mix series, the Modulus values decreased at the age of 28 days with the addition of SF as much as 2% to 10% compared to CM. The values corresponded to the characteristic of concrete where it is weak in tension condition.

For the 'Designed' Mixes (E- Compressive Modulus), in Table 4.16, in every mix series, the Modulus values were high and increased at the age of 28 days with the addition of SF as much as 10% to 40% compared to CM. The values corresponded to the characteristic of concrete where it is good in compression.

Table 4.17: Modulus of Elasticity – 'As-supplied' Mixes

Mix Series ('As-supplied')	E - Flexural Modulus (GPa)	E - Compressive Modulus (GPa)
250CM	12.35	13.02
250CM	12.00	14.80
250SF5	12.2	16.33
250SF10	12.33	14.94
275CM	12.35	16.35
275SF5	10.51	17.65
350CM	12.17	14.43
350SF5	11.86	16.62
350SF10	11.14	20.00
400CM	10.84	13.05
400SF5	11.44	17.13
400SF10	11.70	20.96

For 'As-supplied' Mixes (E- Flexural Modulus), compared with 'Designed' mixes in Table 4.17, in this mix, the Modulus values also decreased and were lower 35% at the age of 28 days. With the addition of SF, the modulus values of SF5 and SF10 have decreased compared to CM as much as 2% to 5%. The values corresponded to the characteristic of concrete where it is weak in tension condition.

For 'As-supplied' Mixes (E- Compressive Modulus), compared with 'Designed' mixes in Table 4.18, in every mix series, the compressive modulus values obtained were lower by 35% and increased at the age of 28 days with the addition of SF as much as 7% to 38% compared to CM. The values corresponded to the characteristic of concrete where it is good in compression.

In overall, the concrete produced were deformation resistance. No obvious changes in values occurred although the cement content was increased in every mix series. OPC was not the main consideration in high modulus values in concrete. Well graded and finely distributed aggregates were considered. To predict the E-Modulus in concrete, it is good to have the ideal designed aggregate contents and segregation as well as their compressive strength (W. Baalbaki, 1997).

Concretes which have the same compressive strength and made of various types of aggregates have different E-Modulus values. The compressive strength varied because of the properties of the aggregate sizes and distribution (P.C. Aitcin, 2003). Thus as proposed, Series 1 (250 kg/m^3) was the ideal mix design. The results were shown in Figure 4.25.

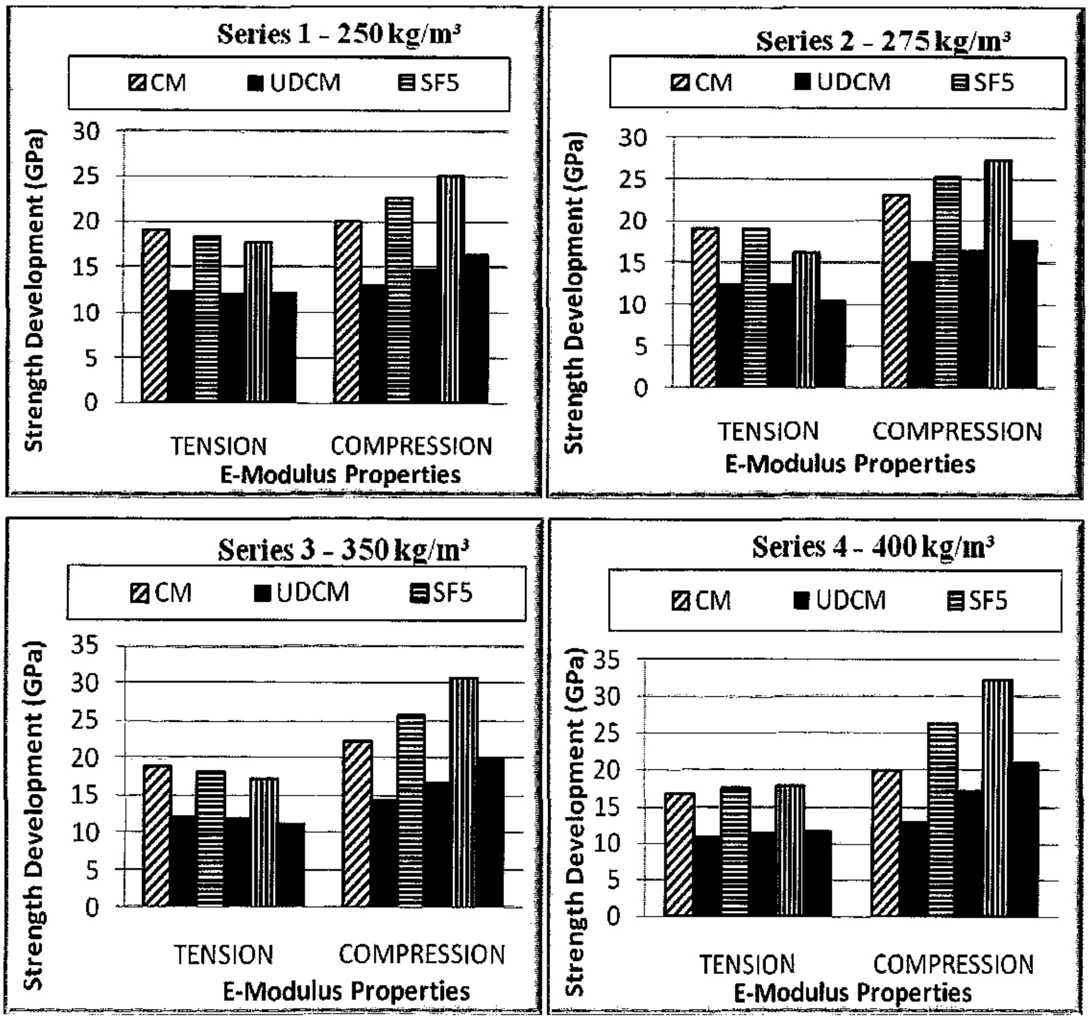


Figure 4.25: Modulus of Elasticity – 'Designed' and 'As-supplied' Mixes.

The mix design produced fulfilled the characteristic of concrete that is weak in tension conditions. From this, designers were able to estimate the deformation limit which is the modular ratio, n, in structures and structural elements (columns and beams) (T. Tomosawa and M. Nogouchi, 1997).

4.4. Efficiency Analysis.

The following sub-sections discussed the result analysis for the efficiency of the concrete mixes with respect to the eco-friendliness and the green technology requirements. Since the 'Designed' mixes has better performance in potential durability, detail analysis were focused and discussed in the following sub-sections.

4.4.1. Cement Consumption in Mixes

The cement consumed in mix series were considered in two sections

1. Mixes with 100% OPC (Table 4.20)
2. Mixes with 100 % OPC, 5% SF and 10% SF (Table 4.21)

The sections were illustrated in a Matrix Efficiency Table which was Table 4.18 and Table 4.19.

Table 4.18: Matrix Efficiency – 100% OPC

COST	CEMENT CONSUMPTION (KG/M³/MPa)										
(RM/MPa/M³)	4.0 - 4.5	4.5 - 5.0	5.0 - 5.5	5.5 - 6.0	6.0 - 6.5	7.0 - 7.5	7.5 - 8.0	8.0 - 8.5	8.5 - 9.0	9.0 - 9.5	9.5 - 10.0
5.00 - 5.50	LT-A										
5.50 - 6.00											
6.00 - 6.50	LT-B										
6.50 - 7.00			LT-C	LT-D	R1-A, R3-B, R4-B, R5-C		R5-B				
7.00 - 7.50					R1-B, R2-A, R2-C						
7.50 - 8.00					R2-B, R4-A						
8.00 - 8.50		R4-C			R1-C	R3-C					
8.50 - 9.00						R5-A					
9.00 - 9.50											
9.50 - 10.00											
10.00 - 10.50											
10.50 - 11.00											
11.00 - 11.50											[illegible]

ECO-FRIENDLY MIXES
ACCEPTABLE MIXES
NON-ECO-FRIENDLY MIXES

A	SERIES 250 KG/M³	C	SERIES 350 KG/M³
B	SERIES 275 KG/M³	D	SERIES 400 KG/M³

From Table 4.18, with comparison with five other researches, all mixes conducted from Laboratory Test (LT) were eco-friendly mixes. These mixes fulfilled the criteria of being the most effective in cost and low in cement consumption during production.

Table 4.19: Matrix Efficiency – 100% OPC, 5% SF and 10% SF

COST	CEMENT CONSUMPTION (KG/M³/MPa)										
(RM/MPa/M³)	4.0 - 4.5	4.5 - 5.0	5.0 - 5.5	5.5 - 6.0	6.0 - 6.5	6.5 - 7.0	7.0 - 7.5	7.5 - 8.0	8.0 - 8.5	8.5 - 9.0	9.0 - 9.5
4.00 - 4.50	A1										
4.50 - 5.00											
5.00 - 5.50											
5.50 - 6.00	B1										
6.00 - 6.50	A2, A3, B2								[illegible]		
6.50 - 7.00	B3	D3	C1							[illegible]	
7.00 - 7.50		C3, RI-3, RI-6, RI-9	C2	RI-5, RI-8	RI-17						
7.50 - 8.00		RI-14		D2	D1						
8.00 - 8.50				RI-2	RI-18		RI-7				
8.50 - 9.00	RI-15						RI-16	RI-12			
9.00 - 9.50											
9.50 - 10.00											
10.00 - 10.50											
10.50 - 11.00											RI-13
11.00 - 11.50										RI-11	RI-10

(white)	ECO-FRIENDLY MIXES	A	SERIES 250 KG/M³	1	CM
(grey)	ACCEPTABLE MIXES	B	SERIES 275 KG/M³	2	SF5
(dark)	NON-ECO-FRIENDLY MIXES	C	SERIES 350 KG/M³	3	SF10
		D	SERIES 400 KG/M³		

From Table 4.19, with comparison with other research, most mixes conducted from this research were eco-friendly mixes. Eco-friendly as defined by the Environmental Council of Concrete Organization, 2006, as something that is doing good to the environment not giving any negative effects. In this research, the efficiency table is produced by taking into consideration the cement consumption and the cost of produced concrete. The tables were used as standards of determination where the objective is to have less cement as possible in the produced concrete with maintained high strength. These mixes fulfilled the criterias of being the most effective in cost and low in cement consumption during production.

As mentioned, comparisons were done with other researchers in both conditions based on the approximate same amount of cement content used in their mixes and the approximate similar compressive strength of 28 days. Table 4.20 showed the results of 100% OPC comparison and was illustrated in Figure 4.26 while Table 4.21 showed the results of 100% OPC, 5% SF and 10% SF comparison, illustrated in Figure 4.27.

Table 4.20: 100% OPC Comparisons

Mix Samples	Cement Content (kg/m^3)	Cement Consumption ($kg/m^3/MPa$)
Current Research LT (Laboratory Test, 2010)	**A - 250 kg/m^3**	4.02
	B - 275 kg/m^3	4.34
	C - 350 kg/m^3	5.20
	D - 400 kg/m^3	5.80
R1 (M.G. Alexander & B.J. Magee, 1999)	**A - 265 kg/m^3**	5.96
	B - 315 kg/m^3	5.53
	C - 360 kg/m^3	5.63
R2 (G.C. Isaia *et.al.*, 2003)	**A - 367 kg/m^3**	6.17
	B - 428 kg/m^3	6.05
	C - 367 kg/m^3	6.17
R3 (J. Lindgard & S. Smeplass, 1992)	**A - 648 kg/m^3**	9.83
	B - 455 kg/m^3	5.75
	C - 586 kg/m^3	6.87
R4 (F. de-Larrard & R.LeRoy, 1992)	**A - 426 kg/m^3**	6.34
	B - 412 kg/m^3	5.52
	C - 422 kg/m^3	4.52
R5 (G.G. Carette & V.M. Malhotra, 1992)	**A - 410 kg/m^3**	7.26
	B - 524 kg/m^3	7.90
	C - 478 kg/m^3	5.67

Figure 4.26 showed that mixes conducted in this research consumed less cement compared to other researchers. Research mixes saved approximately 25% of cement consumption during production. With reduced cement content, high strength in concrete has achieved compared with other researchers who used more cement to achieve the required high strength.

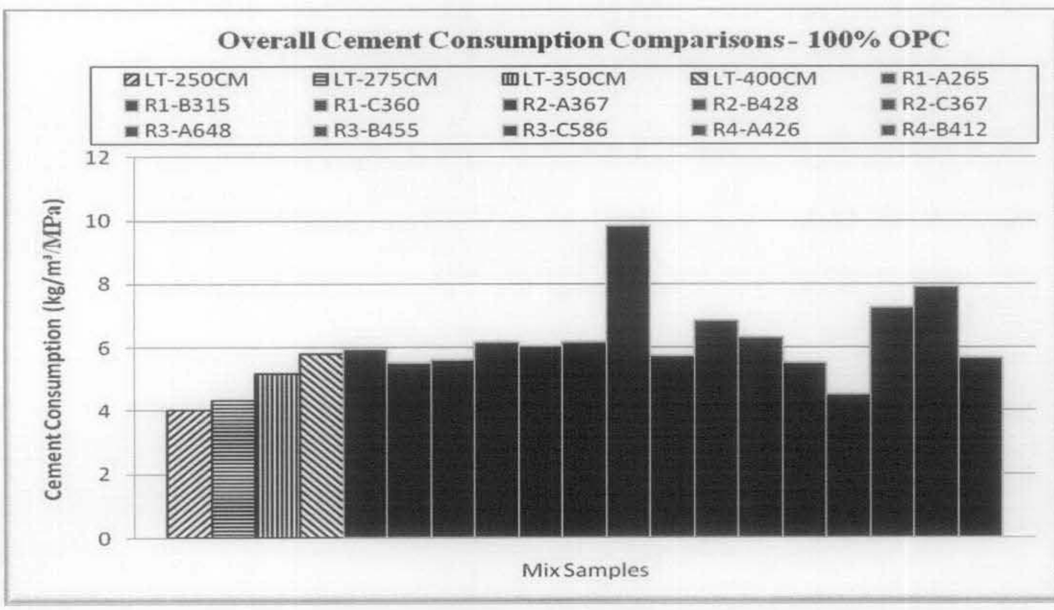


Figure 4.26: Overall Cement Consumption Comparisons – 100% OPC

Table 4.21: 100% OPC, 5%SF and 10% SF Comparisons

Mix Samples	Cement Content (kg/m^3)	Cement Consumption ($kg/m^3/MPa$)
Current Research LT (Laboratory Test, 2010)	**250 kg/m^3**	4.03
		4.02
		4.01
	275 kg/m^3	4.40
		4.34
		4.32
	350 kg/m^3	5.42
		5.20
		4.95
	400 kg/m^3	6.32
		5.80
		4.70
R1 (M.G. Alexander & B.J. Magee, 1999)	**265 kg/m^3**	8.55
		5.96
		4.73
R2 (M.G. Alexander & B.J. Magee, 1999)	**315 kg/m^3**	8.08
		5.53
		4.70
R3 (M.G. Alexander & B.J. Magee, 1999)	**360 kg/m^3**	7.06
		5.63
		4.80
R4 (G.G. Carette & V.M. Malhotra, 1992)	**410 kg/m^3**	9.00
		8.56
		7.70
R5 (W. Baalbaki *et.al*, 1992)	**450 kg/m^3**	9.06
		6.20
		5.50
R6 (G.G. Carette & V.M. Malhotra, 1992)	**480 kg/m^3**	7.24
		6.50
		5.87

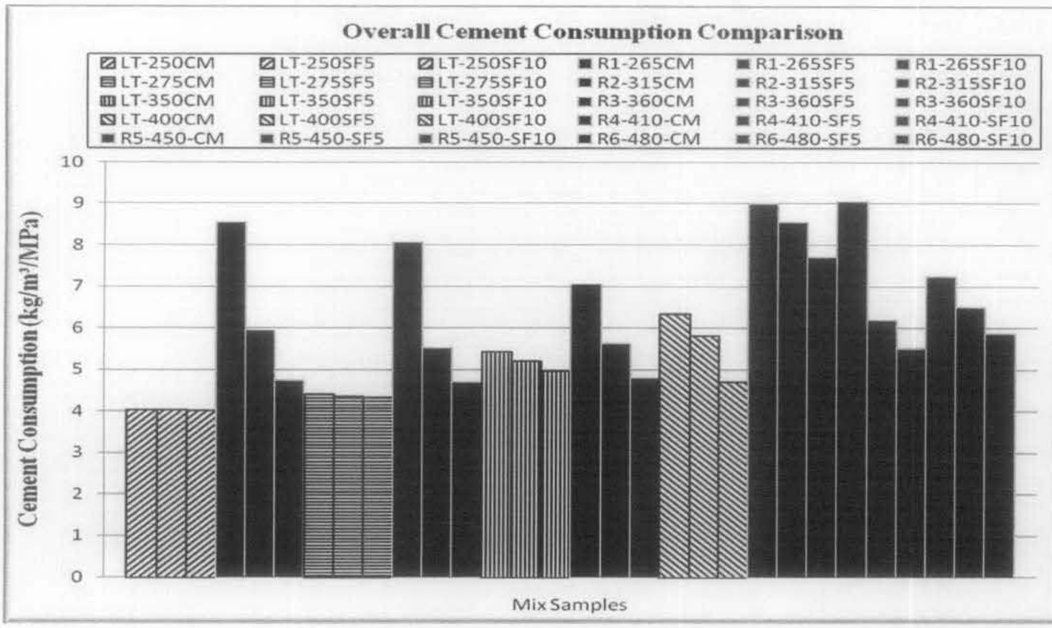


Figure 4.27: Cement Consumption Comparisons – 100% OPC, 5% SF and 10% SF

Figure 4.32 showed that mixes in this research consumed less cement compared to other researchers. Research mixes saved approximately 60% of cement consumption during production. With reduced cement content, high strength in concrete has achieved compared with other researchers who used more cement to achieve the required high strength.

Cement content was not the main contribution to high strength in concrete but also depended on the aggregates and SF addition. With the addition of SF into the concrete mixes, as much as 20% of OPC was saved from consumption for this research.

4.4.1.1 Cement Efficiency in Mix Series

The cement efficiency (kg/m³/MPa) were arranged and compared in Table 4.22. The results were illustrated in Figure 4.28.

Table 4.22: Cement Efficiency (kg/m³/MPa) Comparisons

Compressive Strength 28 Days (MPa)	Research					
	LT	R1	R2	R3	R4	R5
	Feasibilty (kg/m³/MPa)					
60-70	4.30	4.73	6.20	6.34	7.26	9.83
70-80	4.95	4.70	6.05	5.52	7.90	5.75
80-90	4.70	4.80	4.85	4.52	5.67	6.87

Legends

LT	Current Research (2010)
R1	M.G. Alexander & B.J. Magee (1999)
R2	G.C. Isaia et.al (2001)
R3	F. de-Larrard & R. LeRoy (1992)
R4	G.G. Carrette & V.M. Malhotra (1992)
R5	J. Lingard & S. Smeplass (1992)

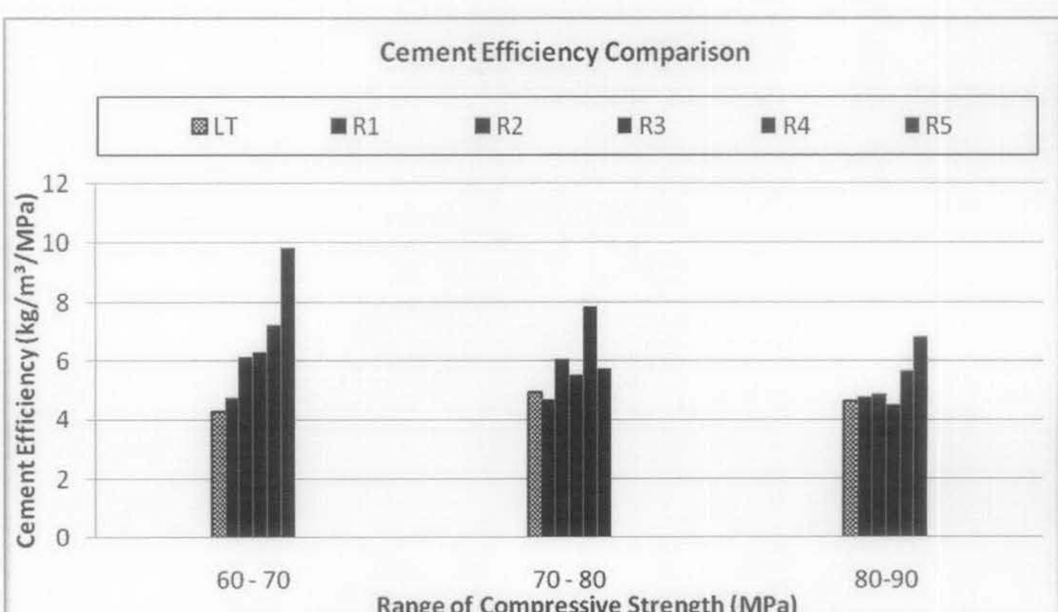


Figure 4.28: Cement Efficiency (kg/m³/MPa) Comparisons

In Figure 4.28, the cement efficiency of the research mixes were low. This was so as less cement was used. The amount of cement consumed were the lowest compared to other researchers. High cement efficiency results in low cement consumption in production. Concrete mixtures are to be modified to achieve less porosity, reduced cracking potentials and increased strength. The handling characteristics and workability are to be maintained (Narotam *et.al*, 2003). Thus, with reduced cement content, research mixes has achieved high compressive strength within the range of 60MPa to 90MPa.

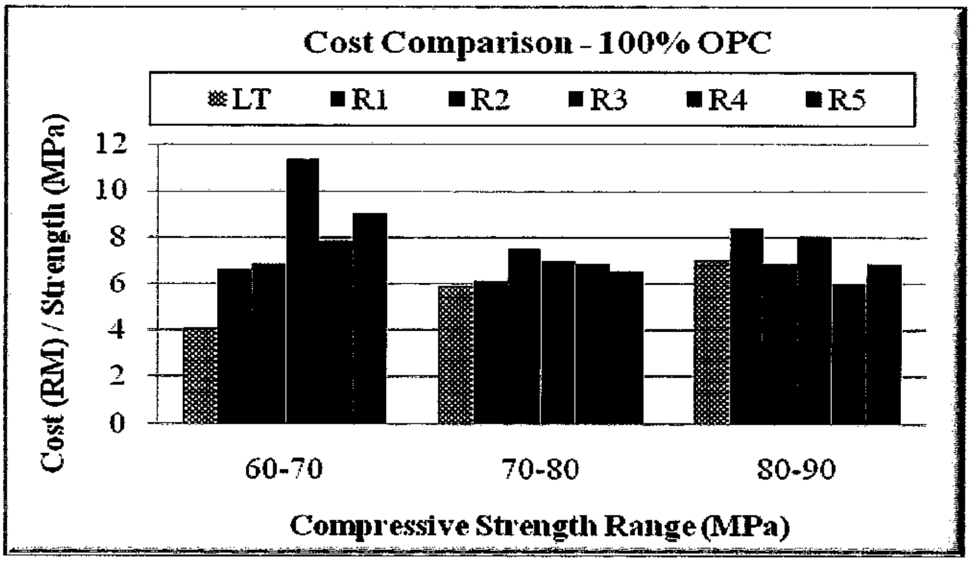
4.4.2. Economic Considerations (Cost Analysis)

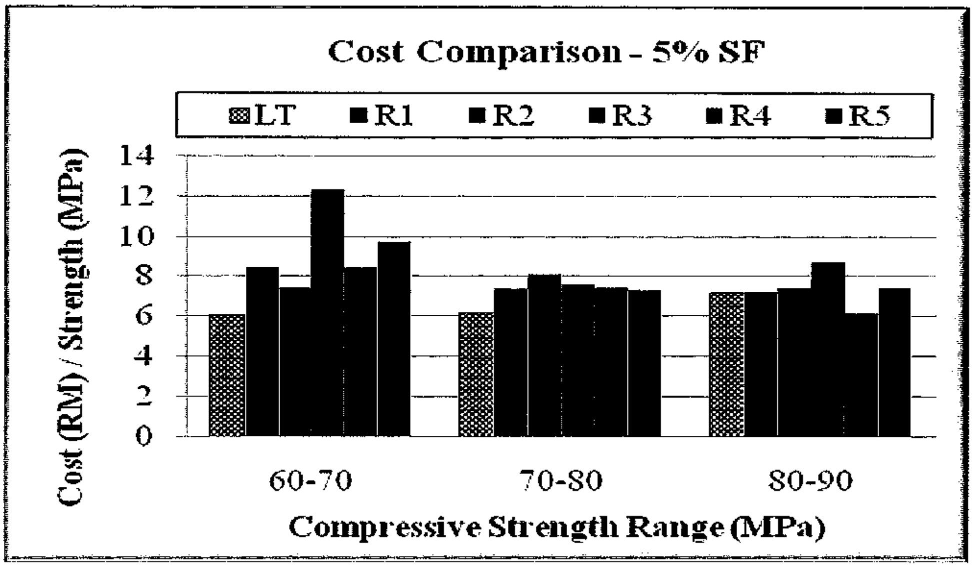
The economic consideration is very important so that time and money can be save catering for fast pace construction. The results were obtained from simple calculations and were arranged in Table 4.23. The cost was compared in terms of 3 compressive strength ranges that were 60-70 MPa, 70-80 MPa and 80-90 MPa.

Comparisons are made with other research based on approximate similar compressive strength of 28 days and cement content as well as the cement replacing material used, SF. The results are as shown from Figure 4.34. Figure 4.35 displayed the overall cost effectiveness of the research with other researchers.

Table 4.23: Cost Effectiveness between cost and compressive strength (RM/MPa)

Mix Series	**LT - 250**	**LT - 275**	**LT - 350**	**R1 - 265**	**R1 - 315**	**R1 - 360**
Mix Samples	**LT -1**	**LT-2**	**LT -3**	**R1 - 1**	**R1-2**	**R1-3**
100 % OPC	4.11	5.93	7.05	6.64	6.13	8.40
5 % SF	6.03	6.19	7.20	8.45	7.40	7.22
10 % SF	6.34	6.51	7.30	7.41	7.06	7.00
Mix Series	**R2 - 367**	**R2 - 428**	**R2 - 367**	**R3 - 648**	**R3 - 455**	**R3 - 586**
Mix Samples	**R2-1**	**R2-2**	**R2-3**	**R3-1**	**R3-2**	**R3-3**
100 % OPC	6.86	7.48	6.86	11.37	7.02	8.05
5 % SF	7.47	8.10	7.47	12.35	7.60	8.74
10 % SF	8.09	8.70	8.09	13.33	8.20	9.43
Mix Series	**R4 - 426**	**R4 - 412**	**R4 - 422**	**R5 - 410**	**R5 - 524**	**R5 - 478**
Mix Samples	**R4-1**	**R4-2**	**R4-3**	**R5-1**	**R5-2**	**R5-3**
100 % OPC	7.84	6.88	6.00	9.03	6.56	6.87
5 % SF	8.50	7.43	6.13	9.75	7.35	7.44
10 % SF	9.11	8.00	6.60	10.48	8.14	8.00
Legends	R1 - (M.G. Alexander & B.J. Magee, 1999) R2 - (G.C. Isaia *et.al.*, 2003)		R3 - (J. Lindgard & S. Smeplass, 1992) R4 - (F. de-Larrard & R. LeRoy1992)		R5 - (G.G. Carette & V.M. Malhotra, 1992)	





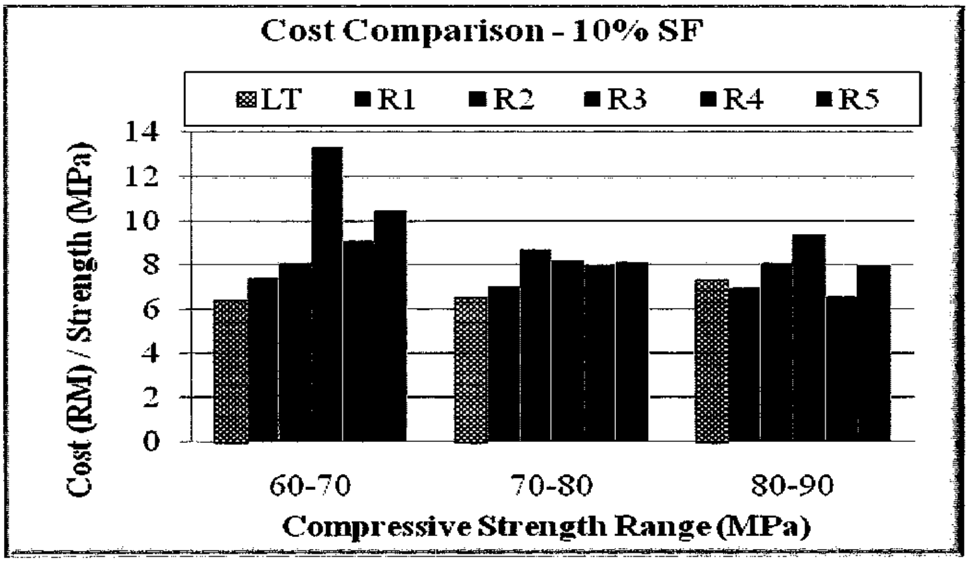


Figure 4.29: Cost Effectiveness (RM/MPa) Comparisons in Mix Series

In overall discussion, Figure 4.29, the range of the cost in every compressive strength, MPa, compared with other researchers was from RM4.00 to RM7.00. Research mixes saved about RM1.00 to RM8.00 in LT mixes, RM1.00 to RM7.00 in mixes with added 5% SF and RM2.00 to RM7.00 in mixes with added 10% SF. Each series has a percentage difference of 30%, 34% and 43%. High percentage values results in huge cost savings. Thus research mixes were very cost effective and feasible in construction applications.

This was so as materials used in this research were natural and locally available. This was proven by H.G. Russell (2000) where stated that the mix proportions for high performance to meet the specified performance criteria at a reasonable cost using locally available materials. The total cost of a produced and finished concrete material is more important than the cost of an individual material. Figure 4.30 showed the overall cost effectiveness of research mixes (LT) with comparisons to other researchers.

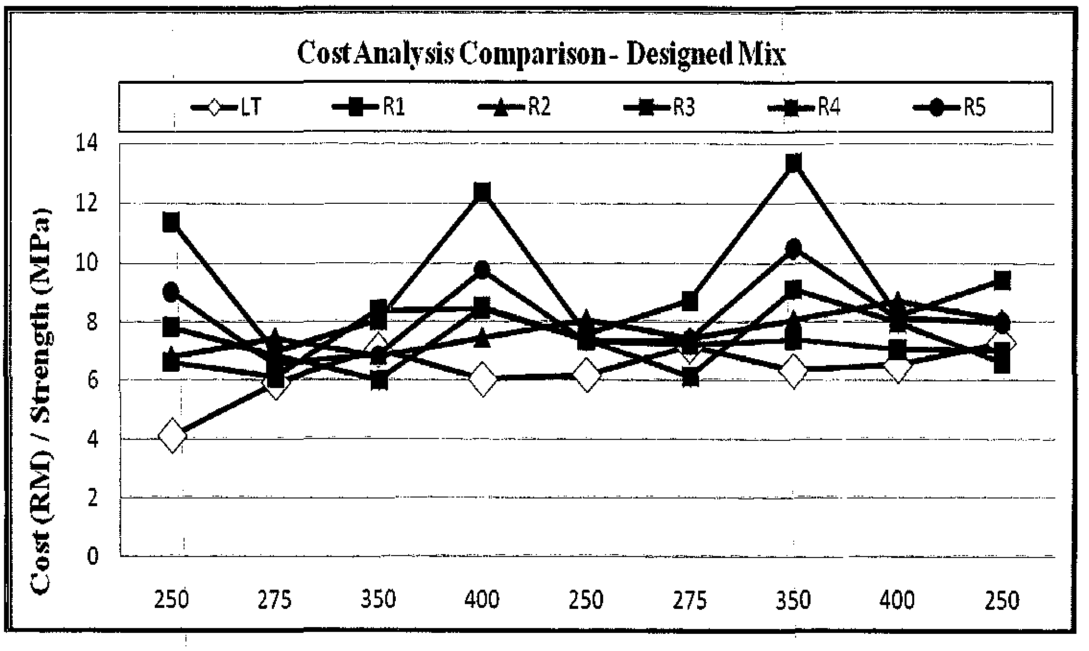


Figure 4.30: Overall Cost Effectiveness (RM/MPa) Comparisons in Mix Series

4.4.3. Energy Consumption

The amount of energy consumed by the mixes during production were calculated. The standard energy table used can be referred in Appendix E. Comparisons with other research are also made to determine the energy efficiency of the mixes. The results were arranged in Table 4.24 and Figure 4.36 shows the efficiency of the amount of energy consumed.

Table 4.24: Energy Consumption Efficiency (kwh/tonne)

Mix Samples	Cement Content	Energy Consumed (kwh/tonne)
Current Research LT (Laboratory Test, 2010)	250 kg/m^3	182
	275 kg/m^3	196
	350 kg/m^3	237
	400 kg/m^3	238
R1 (M.G. Alexander & B.J. Magee, 1999)	265 kg/m^3	191
	315 kg/m^3	218
	360 kg/m^3	243
R2 (G.C. Isaia *et.al.*, 2003)	367 kg/m^3	247
	428 kg/m^3	280
	367 kg/m^3	247
R3 (J. Lindgard & S. Smeplass, 1992)	648 kg/m^3	400
	455 kg/m^3	295
	586 kg/m^3	367
R4 (F. de-Larrard & R. LeRoy, 1992)	426 kg/m^3	279
	412 kg/m^3	271
	422 kg/m^3	277
R5 (G.G. Carette & V.M. Malhotra, 1992)	410 kg/m^3	270
	524 kg/m^3	333
	478 kg/m^3	307

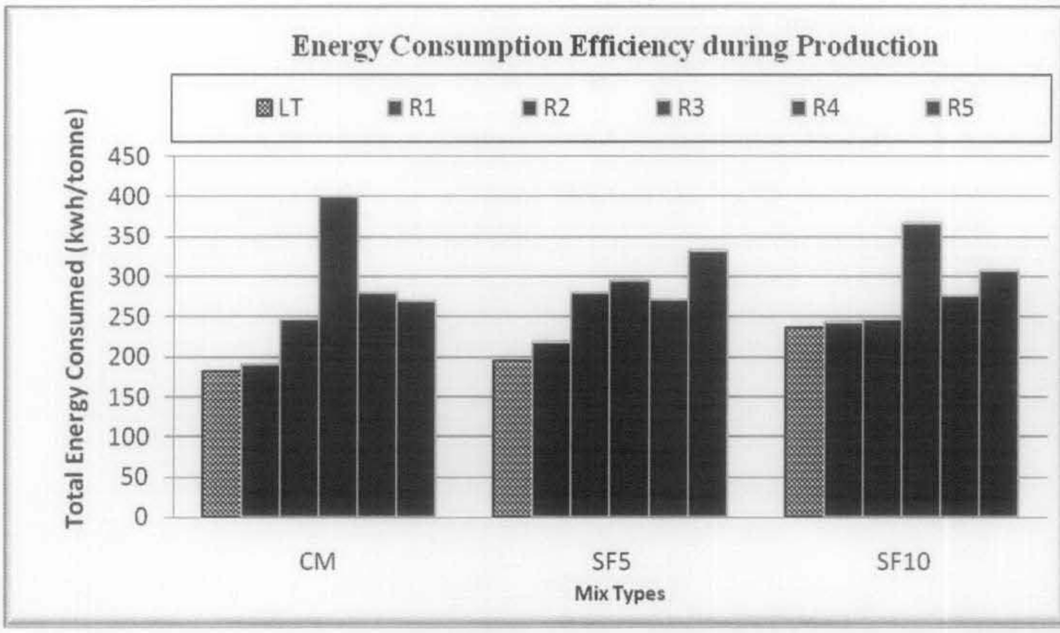


Figure 4.36: Energy Consumption Efficiency

From Figure 4.36, the energy consumed during production by LT were lower compared to other researchers. The increased amount of cement content in mixes consumed more energy during production. This was because more energy was required to create chemical reactions among particles in mixes. LT has saved 21% of energy if compared to R1, 15% from R2, 41% from R3, 15% from R4 and 30% from R5. Thus, LT is energy effective. LT consumed lower energy during production. With approximately same amount of cement used compared to other researchers, LT managed to achieve high strength. Thus cement is not the main contributor to concrete's high strength but also affected by aggregate gradings and SF content in the concrete mix. The addition of SF as CRM has helped in reduced energy consumption where it enhances the hydration of concrete with the added characteristic of the filler effects.

4.4.5. Carbon Dioxide (CO_2) Emissions.

The environmental impact is also another main consideration and it's emission into the atmosphere is a great concern to many parties. In this research, the amount of CO_2 emission is obtained based on the global understanding of 1 tonne of cement produced emits 1 tonne of CO_2 into the atmosphere. The amount of CO_2 is obtained for the three section tests:

1. Cubes (150 mm x150 mm x150 mm) – Compressive Strength Test
2. Cylinders (100 mm diameter, 200 mm Height), Cores (40 mm diameter) and Cubes (100 mm x 100 mm x 100 mm)

   (Tensile Test, Porosity Test and Chloride Migration Test)
3. Prisms (500 mm x 100 mm x 100 mm) – Modulus of Elasticity

Calculations were done from the worksheet in Appendix B, Appendix C and Appendix D created using the Microsoft Excel Software. The results are discussed in the following sub-sections. The percentage of CO_2 emission depends on the type of concrete samples tested from their volumes. This application is most useful in industrial practice where concrete were batched in large quantities.

4.4.5.1. Compressive Strength – Cube Test.

From calculations done from worksheet (Appendix A), this research saved 6% of CO_2 emission with comparison with R1 (M.G. Alexander & B.J. Magee, 1999), 25% with R2 (G.C. Isaia et.al, 2003), 48% with R3 (J. Lindgard & S. Smeplass, 1992), 31% with R4 (F. de-Larrard & R. LeRoy, 1992) and 38% with R5 (G.G. Carrette & V.M. Malhotra, 1992). The percentage values were high. This proved that concrete produced from research is eco-green and have high compressive strength in performance as shown in Table 4.25.

Table 4.25: Amount of CO_2 saved (%) - LT with other research (Cube Test)

Other Research	Amount of CO_2 saved (%) - LT with other research
R1	6
R2	25
R3	48
R4	31
R5	38

4.4.5.2. Potential Durability Performance.

From calculations done from worksheet (Appendix B), this research saved 21% of CO_2 emission with comparison with R1 (M.G. Alexander & B.J. Magee, 1999), 25% with R2 (G.C. Isaia et.al, 2003), 48% with R3 (J. Lindgard & S. Smeplass, 1992), 31% with R4 (F. de-Larrard & R. LeRoy, 1992) and 38% with R5 (G.G. Carrette & V.M. Malhotra, 1992). The percentage values were high. This proved that concrete produced from research is eco-green and is highly durable in performance in terms of porosity, tensile strength and chloride ion migration (marine environment) as shown in Table 4.26;

Table 4.26: Amount of CO_2 saved (%) - LT with other research (Durability Test)

Other Research	Amount of CO_2 saved (%) - LT with other research
R1	21
R2	25
R3	48
R4	31
R5	38

4.4.5.3. Modulus of Elasticity

From calculations done from worksheet (Appendix C), this research saved 6% of CO_2 emission with comparison with R1 (M.G. Alexander & B.J. Magee, 1999), 25% with R2 (G.C. Isaia *et.al*, 2003), 48% with R3 (J. Lindgard & S. Smeplass, 1992), 31% with R4 (F. de-Larrard & R. LeRoy, 1992) and 38% with R5 (G.G. Carrette & V.M. Malhotra, 1992). The percentage values were high. This proved that concrete produced from research is eco-green and is highly flexible in performance. High modulus of elasticity values provides stiffer structure which has less lateral deflection under wind loads (H. Russell, 1999) as shown in Table 4.27;

Table 4.27: Amount of CO_2 saved (%) - LT with other research (E-Modulus)

Other Research	Amount of CO_2 saved (%) - LT with other research
R1	6
R2	25
R3	48
R4	31
R5	38

4.4.5.4. Overall Discussions.

As discussed in previous sub-sections, concrete produced in research have saved huge amount of CO_2 emissions into the atmosphere. Thus concrete is ecological friendly and meets the demand of the society in terms of overcoming environmental crisis where the demand for less pollution in CO_2 emissions is critically required so to reduce the ease of carbon generation within concrete which is important to enhance durability (C.L. Narotam *et.al*, 2003). Concrete produced from research were ideal mix designs.

4. 5. Overall Chapter Discussion.

As an overall for this chapter, mix series samples have good performance in terms of compressive strength, porosity, tensile strength, chloride migration and modulus of elasticity. The mixing was also conducted in proper and no obvious as well as serious micro-cracks occurred during the time of curing and testing. Curing techniques and tests were conducted with accordance to the standard obtained in theory and real-site condition. HPC are specified today to have increased workability, high ultimate strength, high early strength, high durability and high modulus of elasticity (T. Holland, 2009)

The compressive strength results obtained from research were high and increased further after the 28 days age. High early strength was obviously shown by the concrete and the illustrations were illustrated in figures. The concrete's performance is determined by a combination of many factors, not only depending on the amount of OPC used and types of CRM but also the aggregates, well graded and finely distributed (C.L. Narotam *et.al*, 2003). Concrete compressive strength is closely related to the compactness of the hardened matrix (R. Feret, 1892). Thus, when compressive strength is limited by aggregates, the only way to get higher strength is to use well graded and finely distributed aggregates (P.C. Aitcin, 2003). Cement content is no more the major concern that affects the concrete strength and high early strength.

The concrete also have great performance in potential durability. It is low in porosity efficiency, high in tensile strength, low chloride ion penetration in both urban and marine environment and high modulus of elasticity. To tackle for economic, energy crisis and environmental concerns, the mix designs were cost effective, energy efficient, and eco-friendly. According to A.M. Fouzi and B. Mouloud (2007), more slender structural elements, more audacious designs and the service life for HPC should exceed that of ordinary concrete in the same environment are very critically in demand.

The addition of SF has contributed greatly to the early compressive strength and the strength development in concrete. SF played the role as an ideal CRM. CRM working with OPC improves strength and durability when added during mixing. Reduction of CO_2 by 70% is possible with CRM typical usage values ranging between 15% and 40% (M.A. Iyad *et.al*, 1997). For each concrete strength level, there is an optimum size for the aggregates that will yield the greatest compressive strength per unit mass of cement. A smaller size aggregate will result in higher compressive strength of concrete. The use of largest possible coarse aggregate size is important in increasing the modulus of elasticity (H.G. Russell, 2000)

Worksheets were produced using the Microsoft Excel Software. This is to ease designers in calculations during production (custom or industrial). K. Day (1993) mentioned that laboratory trial mixes may be very useful but for some purposes, computerization is really required in major ready-mix organization as there are hundreds of mixes in dozens of plants with many alternative materials.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

For this research study, the principal objectives were focused to obtain high compressive strength of 28 days age (50MPa – 80MPa), high performance and 'eco-green' concrete for the future construction industry. Well graded and finely distributed aggregates with reduced cement content were the main considerations to achieve the principal objective. In view of this, a detail experimental program was designed and the results as obtained were discussed for the different behavior of concrete that incorporated SF of different dosages which also acts as the cement replacing material (CRM). It was then compared with the behavior of normal conventional concrete mixes which were the control mixes (CM). Later, the cost effectiveness, energy efficiency during production and CO_2 emissions were determined. Based on results and discussions, the following conclusions were drawn;

1. Chemical compositions of OPC and SF obtained were similar to the chemical compositions of the control mixes. There were no hazardous and/or detrimental products such as chloride, heavy metals and excessive alkalis were traced.

2. Well graded and finely distributed aggregates in concrete mixes (good aggregate gradings) were the main objective This was well shown in the 'Designed' mixes and 'As-supplied' mixes. The British Standard (BS) was used as the basic for the mix design proportions. The coarse aggregates were not changed in proportions as the objective specified well graded and finely distributed aggregates for this investigation. The sizes of the coarse

aggregates used were standard 20mm diameter maximum from the same aggregate source.

3. The compressive strength of concrete produced was determined by a fix water cementatious ratio and a constant amount of superplasticizer (SP) was used throughout this investigation. The slump was fixed in the range of 40mm – 70mm. The compressive strength achieved by the 'Designed' mixes were 20% and is better than the 'As-supplied' mixes when compared to CM in every mix series. With the addition of SF, at 28 days age compressive strength achieved by SF5 was approximately 16% - 40% higher and 12% -50% higher in SF10. After the 28 days age, 5% - 10% of strength increment was obvious especially with the addition of SF.

4. The high early strength of 3 and 7 days age achieved were 5%-10% higher with comparison with the CM mixes in every mix series. At 3 days age, SF5 and SF10 mixes achieved compressive strength of more than 40MPa. The research has fulfilled the main objective in obtaining high strength high performance concrete between strength of 50MPa – 80MPa. The application of well graded and finely distributed aggregates with reduced cement content and SF as CRM and additive had contributed well throughout this investigation.

5. The total porosity development of concrete in both mixes was ideal. The porosity development reduced with age. Between both mixes, 'Designed' mixes performed better 2%-10% in CM. With SF added, porosity reduced by 3%-4% for both mixes. Low porosity is better as it will increase concrete's durability. Thus, 'Designed' mixes performed better than 'As- supplied' mixes in reduced cement content condition and also in well graded and finely distributed aggregates condition.

6. Tensile strength achieved by 'Designed' mixes was 20% higher in CM, 30%-35% higher in SF5 and 52% - 72% higher in SF10 in every mix series. High tensile strength values were obtained in 28 days age where almost all values were more than 2MPa. The concrete produced by research has high chance of resistance against cracking.

7. Besides taking into consideration the urban construction, the marine environment was also considered to cater for research flexibility and reliability. Concrete produced by research has high durability against chloride ion penetration. Maximum increase of 20% which is 15mm penetration was obtained throughout the investigation. This showed slow rate of penetration depth of chloride in concrete. The 'Designed' mixes performed better 5% - 20% than the 'As-supplied' mixes. With SF added, the rate of chloride ion penetration into concrete after 28 days slowed down. This proved that cement content was not the main contribution to high durability. High durability also depended on the well graded and finely distributed aggregates of the mix proportions. Research is flexible in the marine environment.

8. The Modulus of Elasticity achieved by 'Designed' mixes was 5%-20% better than the 'As-supplied' mixes in CM mixes. When 5% SF was added, 'Designed' mixes achieved 5%-40% higher than 'As-supplied' mixes. With 10% addition of SF the modulus values of 'Designed' mixes increased greatly as much as 5%-60% compared to 'As-supplied' mixes. . Concrete produced from research is good in compression, high resistance to deformation but very poor in tension condition as tension values obtained from machine were low.

9. From the development of the potential durability and strength achievements of the 2 main mix designs; 'Designed' mixes and 'As-supplied' mixes, 'Designed' mixes were considered to be the ideal mix design. Thus, in terms of cost effectiveness, energy consumption during production and CO_2 emissions, with the assistance of worksheets produced, concrete produced from research saved approximately RM8/m^3 in CM mixes and approximately RM7/m^3 in mixes with added SF with comparison with other research. There was also energy saving during production as much as 15%-41% and reduces CO_2 emissions by approximately 50% compared with the standard global CO_2 emission statistics.

10. The Matrix Efficiency Chart and Worksheets created from simple programming knowledge was utilized to conduct the analysis of this investigation. They were created to ease the designers in calculating structural designs. This is also another effort not to loose the engineering and structural behavior of concrete produced where it is to be high strength, high performance, high durability and 'eco-green'. (Refer to Appendices).

11. As an overall, the optimum mix proportion that was obtained from this research was based on the compressive strength and SF addition which also acts as the CRM in mix samples. It comprises of

Mix Type	:	'Designed' aggregate mixes
OPC TYPE 1	:	250 kg/m^3
Silica Fume (SF)	:	25 kg/m^3
Water	:	113 kg/m^3
Fine Aggregates	:	860 kg/m^3
Coarse Aggregates	:	1290 kg/m^3
w/c	:	0.50

12. It is recommended that in further investigations in this area to continue in order to investigate in detail the potential of this research. The future recommendations are as below:

- The research could include detail investigation of micro-cracks effects, Loadings in different conditions effects and thermal as well as surface permeability effects of High Performance Eco-Green concrete in four climate seasons and fire conditions.

- The research should be conducted in detailing effects with SF as a major role in being the ideal CRM in concrete mixes.

- Application of various types of other technologies should be applied such as aerospace and Nanotechnology in terms of changing the material properties for better production of concrete.

- Simple computer models and fun worksheets should be introduced for portability and mobility.

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APPENDIX A

AMOUNT OF OPC AND CO_2 EMISSION SAVED FROM RESEARCH (COMPRESSIVE STRENGTH)

R1: M.G. Alexander and B.J. Magee (1999).

THE DEVELOPMENT OF HIGH PERFORMANCE ECO-GREEN CONCRETE MIXES

Cement Consumption cum Carbon Dioxide (CO2) Emission Calculation Worksheet

Prepared by : Foong Kah Yen (Cheryl) Checked by : Assoc Prof. Dr. Nasir Shafiq July 2009

Welcome !!! Welcome !!!

START CALCULATING YOUR CO2 EMISSION & SEE HOW MUCH YOU CAN SAVE

Step 1 : Enter mix sample volumes.

Volume of mix samples (Enter Value) 0.00338 m^3

Step 2 : Enter Research Cement Consumption

		Enter cement consumed				
Cement Consumed in Research	1	250	kg/m^3	=	0.85	kg
	2	275	kg/m^3	=	0.93	kg
	3	350	kg/m^3	=	1.18	kg
	4	400	kg/m^3	=	1.35	kg
Cement Consumed in Other Research	1	265	kg/m^3	=	0.90	kg
	2	315	kg/m^3	=	1.06	kg
	3	360	kg/m^3	=	1.22	kg
	4	410	kg/m^3	=	1.39	kg

Step 3 : Enter values to determine no. of samples for every series

No. of testing days for mix samples	(Enter Value)	=	4	days
No. of mix samples required for each testing days	(Enter Value)	=	3	mixes
	TOTAL	=	**12**	samples
No. of sets for each series	(Enter Value)	=	3	series
	TOTAL	=	**36**	samples for every series

Total Cement Consumed in each Mix Series / **Converting kg to Tonne**

	kg	kg		Tonne	Tonne
1	30.42	32.25	1	0.03	0.03
2	33.46	38.33	2	0.03	0.04
3	42.59	43.80	3	0.04	0.04
4	48.67	49.89	4	0.05	0.05

Your Cement Consumption & Carbon Dioxide Emission are discovered !!! The Values are as shown:

	Tonne	Tonne		kg	kg
1	0.030	0.03	1	30.42	32.25
2	0.033	0.04	2	33.46	38.33
3	0.043	0.04	3	42.59	43.80
4	0.049	0.05	4	48.67	49.89

The total cement consumed & CO_2 emission from Research Study : 155.14 **kg**

The total cement consumed & CO_2 emission from Other Research : 164.27 **kg**

% Difference >>> 5.56 %

CONGRATULATIONS !!!! CONGRATULATIONS !!!

You have helped to save cement consumption & CO2 emission by >> **6** %

HAPPY SAVING & HAVE A GREAT DAY !!! :):)

R2: Isaia *et.al* (2003).

THE DEVELOPMENT OF HIGH PERFORMANCE ECO-GREEN CONCRETE MIXES

Cement Consumption cum Carbon Dioxide (CO2) Emission Calculation Worksheet

Prepared by : Foong Kah Yen (Cheryl) Checked by : Assoc Prof. Dr. Nasir Shafiq July 2009

Welcome !!! Welcome !!!

START CALCULATING YOUR CO2 EMISSION & SEE HOW MUCH YOU CAN SAVE

Step 1 : Enter mix sample volumes.

Volume of mix samples (Enter Value) 0.00338 m^3

Step 2 : Enter Research Cement Consumption

Enter cement consumed

		Cement (kg/m³)		=	kg	
Cement Consumed in Research	1	250	kg/m³	=	0.85	kg
	2	275	kg/m³	=	0.93	kg
	3	350	kg/m³	=	1.18	kg
	4	400	kg/m³	=	1.35	kg
Cement Consumed in Other Research	1	367	kg/m³	=	1.24	kg
	2	428	kg/m³	=	1.45	kg
	3	367	kg/m³	=	1.24	kg
	4	545	kg/m³	=	1.84	kg

Step 3 : Enter values to determine no. of samples for every series

		=		
No. of testing days for mix samples	(Enter Value)	=	4	days
No. of mix samples required for each testing days	(Enter Value)	=	3	mixes
	TOTAL	=	**12**	samples
No. of sets for each series	(Enter Value)	=	3	series
	TOTAL	=	**36**	samples for every series

Total Cement Consumed in each Mix Series / **Converting kg to Tonne**

	kg	kg		Tonne	Tonne
1	30.42	44.66	1	0.03	0.04
2	33.46	52.08	2	0.03	0.05
3	42.59	44.66	3	0.04	0.04
4	48.67	66.32	4	0.05	0.07

Your Cement Consumption & Carbon Dioxide Emission are discovered !!! The Values are as shown:

	Tonne	Tonne		kg	kg
1	0.030	0.04	1	30.42	44.66
2	0.033	0.05	2	33.46	52.08
3	0.043	0.04	3	42.59	44.66
4	0.049	0.07	4	48.67	66.32

The total cement consumed & CO_2 emission from Research Study : 155.14 **kg**

The total cement consumed & CO_2 emission from Other Research : 207.71 **kg**

% Difference >>> 25.31 %

CONGRATULATIONS !!!! CONGRATULATIONS !!!

You have helped to save cement consumption & CO2 emission by >> **25** %

HAPPY SAVING & HAVE A GREAT DAY !!! :):)

R3: J. Lindgard and S. Smeplass (1992).

THE DEVELOPMENT OF HIGH PERFORMANCE ECO-GREEN CONCRETE MIXES

Cement Consumption cum Carbon Dioxide (CO2) Emission Calculation Worksheet

Prepared by: Foong Kah Yen (Cheryl) Checked by: Assoc Prof. Dr. Nasir Shafiq July 2009

Welcome !!! Welcome !!!

START CALCULATING YOUR CO2 EMISSION & SEE HOW MUCH YOU CAN SAVE

Step 1 : Enter mix sample volumes.

Volume of mix samples (Enter Value) 0.00338 m^3

Step 2 : Enter Research Cement Consumption

		Enter cement consumed				
Cement Consumed in Research	1	250	kg/m^3	=	0.85	kg
	2	275	kg/m^3	=	0.93	kg
	3	350	kg/m^3	=	1.18	kg
	4	400	kg/m^3	=	1.35	kg
Cement Consumed in Other Research	1	455	kg/m^3	=	1.54	kg
	2	586	kg/m^3	=	1.98	kg
	3	648	kg/m^3	=	2.19	kg
	4	750	kg/m^3	=	2.54	kg

Step 3 : Enter values to determine no. of samples for every series

No. of testing days for mix samples	(Enter Value)	=	4	days
No. of mix samples required for each testing days	(Enter Value)	=	3	mixes
	TOTAL	=	**12**	samples
No. of sets for each series	(Enter Value)	=	3	series
	TOTAL	=	**36**	samples for every series

Total Cement Consumed in each Mix Series / **Converting kg to Tonne**

	kg	kg		Tonne	Tonne
1	30.42	55.36	1	0.03	0.06
2	33.46	71.30	2	0.03	0.07
3	42.59	78.85	3	0.04	0.08
4	48.67	91.26	4	0.05	0.09

Your Cement Consumption & Carbon Dioxide Emission are discovered !!! The Values are as shown:

	Tonne	Tonne		kg	kg
1	0.030	0.06	1	30.42	55.36
2	0.033	0.07	2	33.46	71.30
3	0.043	0.08	3	42.59	78.85
4	0.049	0.09	4	48.67	91.26

The total cement consumed & CO_2 emission from Research Study : 155.14 **kg**

The total cement consumed & CO_2 emission from Other Research : 296.78 **kg**

% Difference >>> 47.72 %

CONGRATULATIONS !!!! CONGRATULATIONS !!!

You have helped to save cement consumption & CO2 emission by >> **48** %

HAPPY SAVING & HAVE A GREAT DAY !!! :):)

R4: F. de-Larrard and R. Le-Roy (1992).

THE DEVELOPMENT OF HIGH PERFORMANCE ECO-GREEN CONCRETE MIXES

Cement Consumption cum Carbon Dioxide (CO2) Emission Calculation Worksheet

Prepared by : Foong Kah Yen (Cheryl) Checked by : Assoc Prof. Dr. Nasir Shafiq July 2009

UNIVERSITI TEKNOLOGI PETRONAS

Welcome !!! Welcome !!!

START CALCULATING YOUR CO2 EMISSION & SEE HOW MUCH YOU CAN SAVE

Step 1 : Enter mix sample volumes.

Volume of mix samples (Enter Value) 0.00338 m^3

Step 2 : Enter Research Cement Consumption

		Enter cement consumed				
Cement Consumed in Research	1	250	kg/m^3	=	0.85	kg
	2	275	kg/m^3	=	0.93	kg
	3	350	kg/m^3	=	1.18	kg
	4	400	kg/m^3	=	1.35	kg
Cement Consumed in Other Research	1	412	kg/m^3	=	1.39	kg
	2	422	kg/m^3	=	1.43	kg
	3	426	kg/m^3	=	1.44	kg
	4	600	kg/m^3	=	2.03	kg

Step 3 : Enter values to determine no. of samples for every series

No. of testing days for mix samples	(Enter Value)	=	4	days
No. of mix samples required for each testing days	(Enter Value)	=	3	mixes
	TOTAL	=	**12**	samples
No. of sets for each series	(Enter Value)	=	3	series
	TOTAL	=	**36**	samples for every series

Total Cement Consumed in each Mix Series / **Converting kg to Tonne**

	kg	kg		Tonne	Tonne
1	30.42	50.13	1	0.03	0.05
2	33.46	51.35	2	0.03	0.05
3	42.59	51.84	3	0.04	0.05
4	48.67	73.01	4	0.05	0.07

Your Cement Consumption & Carbon Dioxide Emission are discovered !!! The Values are as shown:

	Tonne	Tonne		kg	kg
1	0.030	0.05	1	30.42	50.13
2	0.033	0.05	2	33.46	51.35
3	0.043	0.05	3	42.59	51.84
4	0.049	0.07	4	48.67	73.01

The total cement consumed & CO_2 emission from Research Study : 155.14 **kg**

The total cement consumed & CO_2 emission from Other Research : 226.32 **kg**

% Difference >>> **31.45** %

CONGRATULATIONS !!!! CONGRATULATIONS !!!

You have helped to save cement consumption & CO2 emission by >> **31** %

HAPPY SAVING & HAVE A GREAT DAY !!! :):)

R5: G.G. Carette and V.M. Malhotra (1992).

THE DEVELOPMENT OF HIGH PERFORMANCE
ECO-GREEN CONCRETE MIXES

Cement Consumption cum Carbon Dioxide (CO2) Emission Calculation Worksheet

Prepared by : Foong Kah Yen (Cheryl) Checked by : Assoc Prof. Dr. Nasir Shafiq July 2009

Welcome !!! Welcome !!!

START CALCULATING YOUR CO2 EMISSION & SEE HOW MUCH YOU CAN SAVE

Step 1 : Enter mix sample volumes.

Volume of mix samples (Enter Value) 0.00338 m^3

Step 2 : Enter Research Cement Consumption

		Enter cement consumed				
Cement Consumed in Research	1	250	kg/m^3	=	0.85	kg
	2	275	kg/m^3	=	0.93	kg
	3	350	kg/m^3	=	1.18	kg
	4	400	kg/m^3	=	1.35	kg
Cement Consumed in Other Research	1	410	kg/m^3	=	1.39	kg
	2	478	kg/m^3	=	1.62	kg
	3	524	kg/m^3	=	1.77	kg
	4	650	kg/m^3	=	2.20	kg

Step 3 : Enter values to determine no. of samples for every series

No. of testing days for mix samples	(Enter Value)	=	4	days
No. of mix samples required for each testing days	(Enter Value)	=	3	mixes
	TOTAL	=	**12**	samples
No. of sets for each series	(Enter Value)	=	3	series
	TOTAL	=	**36**	samples for every series

Total Cement Consumed in each Mix Series / **Converting kg to Tonne**

	kg	kg		Tonne	Tonne
1	30.42	49.89	1	0.03	0.05
2	33.46	58.16	2	0.03	0.06
3	42.59	63.76	3	0.04	0.06
4	48.67	79.09	4	0.05	0.08

Your Cement Consumption & Carbon Dioxide Emission are discovered !!! The Values are as shown:

	Tonne	Tonne		kg	kg
1	0.030	0.05	1	30.42	49.89
2	0.033	0.06	2	33.46	58.16
3	0.043	0.06	3	42.59	63.76
4	0.049	0.08	4	48.67	79.09

The total cement consumed & CO_2 emission from Research Study : 155.14 **kg**

The total cement consumed & CO_2 emission from Other Research : 250.90 **kg**

% Difference >>> 38.17 %

CONGRATULATIONS !!!! CONGRATULATIONS !!!

You have helped to save cement consumption & CO2 emission by >> **38** %

HAPPY SAVING & HAVE A GREAT DAY !!! :):)

APPENDIX B

AMOUNT OF OPC AND CO_2 EMISSION SAVED FROM RESEARCH (POTENTIAL DURABILTY PERFORMANCE)

R1: M.G. Alexander and B.J. Magee (1999).

UNIVERSITI TEKNOLOGI PETRONAS

THE DEVELOPMENT OF HIGH PERFORMANCE ECO-GREEN CONCRETE MIXES

Cement Consumption cum Carbon Dioxide (CO2) Emission Calculation Worksheet

Prepared by : Foong Kah Yen (Cheryl) Checked by : Assoc Prof. Dr. Nasir Shafiq July 2009

Welcome !!! Welcome !!!

START CALCULATING YOUR CO2 EMISSION & SEE HOW MUCH YOU CAN SAVE

Step 1 : Enter mix sample volumes.

Volume of mix samples (Enter Value) 0.007 m^3

Step 2 : Enter Research Cement Consumption

		Enter cement consumed				
Cement Consumed in Research	1	250	kg/m³	=	1.75	kg
	2	275	kg/m³	=	1.93	kg
	3	350	kg/m³	=	2.45	kg
	4	400	kg/m³	=	2.80	kg
Cement Consumed in Other Research	1	265	kg/m³	=	1.86	kg
	2	315	kg/m³	=	2.21	kg
	3	360	kg/m³	=	2.52	kg
	4	680	kg/m³	=	4.76	kg

Step 3 : Enter values to determine no. of samples for every series

No. of testing days for mix samples	(Enter Value)	=	3	days
No. of mix samples required for each testing days	(Enter Value)	=	3	mixes
	TOTAL	=	9	samples
No. of sets for each series	(Enter Value)	=	3	series
	TOTAL	=	27	samples for every series

Total Cement Consumed in each Mix Series / **Converting kg to Tonne**

	kg	kg		Tonne	Tonne
1	47.25	50.09	1	0.05	0.05
2	51.98	59.54	2	0.05	0.06
3	66.15	68.04	3	0.07	0.07
4	75.60	128.52	4	0.08	0.13

Your Cement Consumption & Carbon Dioxide Emission are discovered !!! The Values are as shown:

	Tonne	Tonne		kg	kg
1	0.047	0.05	1	47.25	50.09
2	0.052	0.06	2	51.98	59.54
3	0.066	0.07	3	66.15	68.04
4	0.076	0.13	4	75.60	128.52

The total cement consumed & CO_2 emission from Research Study : 240.98 **kg**

The total cement consumed & CO_2 emission from Other Research : 306.18 **kg**

% Difference >>> 21.30 %

CONGRATULATIONS !!!! CONGRATULATIONS !!!

You have helped to save cement consumption & CO2 emission by >> **21** %

HAPPY SAVING & HAVE A GREAT DAY !!! :):)

R2: Isaia *et.al* (2003).

THE DEVELOPMENT OF HIGH PERFORMANCE ECO-GREEN CONCRETE MIXES

Cement Consumption cum Carbon Dioxide (CO2) Emission Calculation Worksheet

Prepared by : Foong Kah Yen (Cheryl) Checked by : Assoc Prof. Dr. Nasir Shafiq July 2009

Welcome !!! Welcome !!!

START CALCULATING YOUR CO2 EMISSION & SEE HOW MUCH YOU CAN SAVE

Step 1 : Enter mix sample volumes.

Volume of mix samples (Enter Value) 0.007 m^3

Step 2 : Enter Research Cement Consumption

Enter cement consumed

Cement Consumed in Research	1	250	kg/m^3	=	1.75	kg
	2	275	kg/m^3	=	1.93	kg
	3	350	kg/m^3	=	2.45	kg
	4	400	kg/m^3	=	2.80	kg
Cement Consumed in Other Research	1	367	kg/m^3	=	2.57	kg
	2	428	kg/m^3	=	3.00	kg
	3	367	kg/m^3	=	2.57	kg
	4	545	kg/m^3	=	3.82	kg

Step 3 : Enter values to determine no. of samples for every series

No. of testing days for mix samples	(Enter Value)	=	3	days
No. of mix samples required for each testing days	(Enter Value)	=	3	mixes
	TOTAL	=	9	samples
No. of sets for each series	(Enter Value)	=	3	series
	TOTAL	=	27	samples for every series

Total Cement Consumed in each Mix Series / **Converting kg to Tonne**

	kg	kg		Tonne	Tonne
1	47.25	69.36	1	0.05	0.07
2	51.98	80.89	2	0.05	0.08
3	66.15	69.36	3	0.07	0.07
4	75.60	103.01	4	0.08	0.10

Your Cement Consumption & Carbon Dioxide Emission are discovered !!! The Values are as shown:

	Tonne	Tonne		kg	kg
1	0.047	0.07	1	47.25	69.36
2	0.052	0.08	2	51.98	80.89
3	0.066	0.07	3	66.15	69.36
4	0.076	0.10	4	75.60	103.01

The total cement consumed & CO_2 emission from Research Study : 240.98 **kg**

The total cement consumed & CO_2 emission from Other Research : 322.62 **kg**

% Difference >>> 25.31 %

CONGRATULATIONS !!!! CONGRATULATIONS !!!

You have helped to save cement consumption & CO2 emission by >> **25** %

HAPPY SAVING & HAVE A GREAT DAY !!! :):)

R3: J. Lindgard and S. Smeplass (1992).

THE DEVELOPMENT OF HIGH PERFORMANCE ECO-GREEN CONCRETE MIXES

Cement Consumption cum Carbon Dioxide (CO_2) Emission Calculation Worksheet

Prepared by : Foong Kah Yen (Cheryl) Checked by : Assoc.Prof Dr. Nasir Shafiq July 2009

UNIVERSITI TEKNOLOGI PETRONAS

Welcome !!! Welcome !!!

START CALCULATING YOUR CO2 EMISSION & SEE HOW MUCH YOU CAN SAVE

Step 1 : Enter mix sample volumes.

Volume of mix samples (Enter Value) 0.007 m^3

Step 2 : Enter Research Cement Consumption

		Enter cement consumed				
Cement Consumed in Research	1	250	kg/m^3	=	1.75	kg
	2	275	kg/m^3	=	1.93	kg
	3	350	kg/m^3	=	2.45	kg
	4	400	kg/m^3	=	2.80	kg
Cement Consumed in Other Research	1	455	kg/m^3	=	3.19	kg
	2	586	kg/m^3	=	4.10	kg
	3	648	kg/m^3	=	4.54	kg
	4	750	kg/m^3	=	5.25	kg

Step 3 : Enter values to determine no. of samples for every series

No. of testing days for mix samples	(Enter Value)	=	3	days
No. of mix samples required for each testing days	(Enter Value)	=	3	mixes
	TOTAL	=	9	samples
No. of sets for each series	(Enter Value)	=	3	series
	TOTAL	=	27	samples for every series

Total Cement Consumed in each Mix Series / **Converting kg to Tonne**

	kg	kg		Tonne	Tonne
1	47.25	86.00	1	0.05	0.09
2	51.98	110.75	2	0.05	0.11
3	66.15	122.47	3	0.07	0.12
4	75.60	141.75	4	0.08	0.14

Your Cement Consumption & Carbon Dioxide Emission are discovered !!! The Values are as shown:

	Tonne	Tonne		kg	kg
1	0.047	0.09	1	47.25	86.00
2	0.052	0.11	2	51.98	110.75
3	0.066	0.12	3	66.15	122.47
4	0.076	0.14	4	75.60	141.75

The total cement consumed & CO_2 emission from Research Study : 240.98 **kg**

The total cement consumed & CO_2 emission from Other Research : 460.97 **kg**

% Difference >>> 47.72 %

CONGRATULATIONS !!!! CONGRATULATIONS !!!

You have helped to save cement consumption & CO2 emission by >> **48** %

HAPPY SAVING & HAVE A GREAT DAY !!! :):)

R4: F. de-Larrard and R. Le-Roy (1992).

UNIVERSITI TEKNOLOGI PETRONAS

THE DEVELOPMENT OF HIGH PERFORMANCE ECO-GREEN CONCRETE MIXES

Cement Consumption cum Carbon Dioxide (CO2) Emission Calculation Worksheet

Prepared by Foong Kah Yen (Cheryl) Checked by Assoc Prof Dr Nasir Shafiq July 2009

Welcome !!! Welcome !!!

START CALCULATING YOUR CO2 EMISSION & SEE HOW MUCH YOU CAN SAVE

Step 1 : Enter mix sample volumes.

Volume of mix samples (Enter Value) 0.007 m^3

Step 2 : Enter Research Cement Consumption

		Enter cement consumed				
Cement Consumed in Research	1	250	kg/m^3	=	1.75	kg
	2	275	kg/m^3	=	1.93	kg
	3	350	kg/m^3	=	2.45	kg
	4	400	kg/m^3	=	2.80	kg
Cement Consumed in Other Research	1	412	kg/m^3	=	2.88	kg
	2	422	kg/m^3	=	2.95	kg
	3	426	kg/m^3	=	2.98	kg
	4	600	kg/m^3	=	4.20	kg

Step 3 : Enter values to determine no. of samples for every series

No. of testing days for mix samples	(Enter Value)	=	3	days
No. of mix samples required for each testing days	(Enter Value)	=	3	mixes
	TOTAL	=	**9**	samples
No. of sets for each series	(Enter Value)	=	3	series
	TOTAL	=	**27**	samples for every series

Total Cement Consumed in each Mix Series / **Converting kg to Tonne**

	kg	kg		Tonne	Tonne
1	47.25	77.87	1	0.05	0.08
2	51.98	79.76	2	0.05	0.08
3	66.15	80.51	3	0.07	0.08
4	75.60	113.40	4	0.08	0.11

Your Cement Consumption & Carbon Dioxide Emission are discovered !!! The Values are as shown:

	Tonne	Tonne		kg	kg
1	0.047	0.08	1	47.25	77.87
2	0.052	0.08	2	51.98	79.76
3	0.066	0.08	3	66.15	80.51
4	0.076	0.11	4	75.60	113.40

The total cement consumed & CO_2 emission from Research Study : 240.98 **kg**

The total cement consumed & CO_2 emission from Other Research : 351.54 **kg**

% Difference >>> 31.45 %

CONGRATULATIONS !!!! CONGRATULATIONS !!!

You have helped to save cement consumption & CO2 emission by >> **31** %

HAPPY SAVING & HAVE A GREAT DAY !!! :):)

R5: G.G. Carette and V.M. Malhotra (1992).

UNIVERSITI TEKNOLOGI PETRONAS

THE DEVELOPMENT OF HIGH PERFORMANCE ECO-GREEN CONCRETE MIXES

Cement Consumption cum Carbon Dioxide (CO2) Emission Calculation Worksheet

Prepared by: Foong Kah Yen (Cheryl) Checked by: Assoc Prof. Dr Nasir Shafiq July 2009

Welcome !!! Welcome !!!

START CALCULATING YOUR CO2 EMISSION & SEE HOW MUCH YOU CAN SAVE

Step 1 : Enter mix sample volumes.

Volume of mix samples (Enter Value) 0.007 m^3

Step 2 : Enter Research Cement Consumption

		Enter cement consumed				
Cement Consumed in Research	1	250	kg/m^3	=	1.75	kg
	2	275	kg/m^3	=	1.93	kg
	3	350	kg/m^3	=	2.45	kg
	4	400	kg/m^3	=	2.80	kg
Cement Consumed in Other Research	1	410	kg/m^3	=	2.87	kg
	2	478	kg/m^3	=	3.35	kg
	3	524	kg/m^3	=	3.67	kg
	4	650	kg/m^3	=	4.55	kg

Step 3 : Enter values to determine no. of samples for every series

No. of testing days for mix samples	(Enter Value)	=	3	days
No. of mix samples required for each testing days	(Enter Value)	=	3	mixes
	TOTAL	=	**9**	samples
No. of sets for each series	(Enter Value)	=	3	series
	TOTAL	=	**27**	samples for every series

Total Cement Consumed in each Mix Series

	kg	kg
1	47.25	77.49
2	51.98	90.34
3	66.15	99.04
4	75.60	122.85

Converting kg to Tonne

	Tonne	Tonne
1	0.05	0.08
2	0.05	0.09
3	0.07	0.10
4	0.08	0.12

Your Cement Consumption & Carbon Dioxide Emission are discovered !!! The Values are as shown:

	Tonne	Tonne
1	0.047	0.08
2	0.052	0.09
3	0.066	0.10
4	0.076	0.12

	kg	kg
1	47.25	77.49
2	51.98	90.34
3	66.15	99.04
4	75.60	122.85

The total cement consumed & CO_2 emission from Research Study : 240.98 **kg**

The total cement consumed & CO_2 emission from Other Research : 389.72 **kg**

% Difference >>> 38.17 %

CONGRATULATIONS !!!! CONGRATULATIONS !!!

You have helped to save cement consumption & CO2 emission by >> **38** %

HAPPY SAVING & HAVE A GREAT DAY !!! :):)

APPENDIX C

AMOUNT OF OPC AND CO_2 EMISSION SAVED FROM RESEARCH (MODULUS OF ELASTICITY)

R1: M.G. Alexander and B.J. Magee (1999).

UNIVERSITI TEKNOLOGI PETRONAS

THE DEVELOPMENT OF HIGH PERFORMANCE ECO-GREEN CONCRETE MIXES

Cement Consumption cum Carbon Dioxide (CO2) Emission Calculation Worksheet

Prepared by : Foong Kah Yan (Cheryl) Checked by : Assoc Prof. Dr. Nasir Shafiq July 2009

Welcome !!! Welcome !!!

START CALCULATING YOUR CO2 EMISSION & SEE HOW MUCH YOU CAN SAVE

Step 1 : Enter mix sample volumes.

Volume of mix samples (Enter Value) 0.005 m³

Step 2 : Enter Research Cement Consumption

		Enter cement consumed				
Cement Consumed in Research	1	250	kg/m³	=	1.25	kg
	2	275	kg/m³	=	1.38	kg
	3	350	kg/m³	=	1.75	kg
	4	400	kg/m³	=	2.00	kg
Cement Consumed in Other Research	1	265	kg/m³	=	1.33	kg
	2	315	kg/m³	=	1.58	kg
	3	360	kg/m³	=	1.80	kg
	4	410	kg/m³	=	2.05	kg

Step 3 : Enter values to determine no. of samples for every series

No. of testing days for mix samples	(Enter Value)	=	3	days
No. of mix samples required for each testing days	(Enter Value)	=	3	mixes
	TOTAL	=	9	samples
No. of sets for each series	(Enter Value)	=	3	series
	TOTAL	=	27	samples for every series

Total Cement Consumed in each Mix Series / **Converting kg to Tonne**

	kg	kg		Tonne	Tonne
1	33.75	35.78	1	0.03	0.04
2	37.13	42.53	2	0.04	0.04
3	47.25	48.60	3	0.05	0.05
4	54.00	55.35	4	0.05	0.06

Your Cement Consumption & Carbon Dioxide Emission are discovered !!! The Values are as shown:

	Tonne	Tonne		kg	kg
1	0.034	0.04	1	33.75	35.78
2	0.037	0.04	2	37.13	42.53
3	0.047	0.05	3	47.25	48.60
4	0.054	0.06	4	54.00	55.35

The total cement consumed & CO_2 emission from Research Study : 172.13 kg

The total cement consumed & CO_2 emission from Other Research : 182.25 kg

% Difference >>> 5.56 %

CONGRATULATIONS !!!! CONGRATULATIONS !!!

You have helped to save cement consumption & CO2 emission by >> **6** %

HAPPY SAVING & HAVE A GREAT DAY !!!):)

R2: Isaia *et.al* (2003).

UNIVERSITI TEKNOLOGI PETRONAS

THE DEVELOPMENT OF HIGH PERFORMANCE ECO-GREEN CONCRETE MIXES

Cement Consumption cum Carbon Dioxide (CO2) Emission Calculation Worksheet

Prepared by : Foong Kah Yen (Cheryl) Checked by : Assoc Prof. Dr. Nasir Shafiq July 2009

Welcome !!! Welcome !!!

START CALCULATING YOUR CO2 EMISSION & SEE HOW MUCH YOU CAN SAVE

Step 1 : Enter mix sample volumes.

Volume of mix samples (Enter Value) 0.005 m^3

Step 2 : Enter Research Cement Consumption

		Enter cement consumed				
Cement Consumed in Research	1	250	kg/m^3	=	1.25	kg
	2	275	kg/m^3	=	1.38	kg
	3	350	kg/m^3	=	1.75	kg
	4	400	kg/m^3	=	2.00	kg
Cement Consumed in Other Research	1	367	kg/m^3	=	1.84	kg
	2	428	kg/m^3	=	2.14	kg
	3	367	kg/m^3	=	1.84	kg
	4	545	kg/m^3	=	2.73	kg

Step 3 : Enter values to determine no. of samples for every series

No. of testing days for mix samples	(Enter Value)	=	3	days
No. of mix samples required for each testing days	(Enter Value)	=	3	mixes
	TOTAL	=	**9**	samples
No. of sets for each series	(Enter Value)	=	3	series
	TOTAL	=	**27**	samples for every series

Total Cement Consumed in each Mix Series / **Converting kg to Tonne**

	kg	kg		Tonne	Tonne
1	33.75	49.55	1	0.03	0.05
2	37.13	57.78	2	0.04	0.06
3	47.25	49.55	3	0.05	0.05
4	54.00	73.58	4	0.05	0.07

Your Cement Consumption & Carbon Dioxide Emission are discovered !!! The Values are as shown:

	Tonne	Tonne		kg	kg
1	0.034	0.05	1	33.75	49.55
2	0.037	0.06	2	37.13	57.78
3	0.047	0.05	3	47.25	49.55
4	0.054	0.07	4	54.00	73.58

The total cement consumed & CO_2 emission from Research Study : 172.13 **kg**

The total cement consumed & CO_2 emission from Other Research : 230.45 **kg**

% Difference >>> **25.31** %

CONGRATULATIONS !!!! CONGRATULATIONS !!!

You have helped to save cement consumption & CO2 emission by >> **25** %

HAPPY SAVING & HAVE A GREAT DAY !!! :):)

R3: J. Lindgard and S. Smeplass (1992).

THE DEVELOPMENT OF HIGH PERFORMANCE ECO-GREEN CONCRETE MIXES

Cement Consumption cum Carbon Dioxide (CO2) Emission Calculation Worksheet

Prepared by : Foong Kah Yen (Cheryl) Checked by : Assoc Prof. Dr. Nasir Shafiq July 2009

Welcome !!! Welcome !!!

START CALCULATING YOUR CO2 EMISSION & SEE HOW MUCH YOU CAN SAVE

Step 1 : Enter mix sample volumes.

Volume of mix samples (Enter Value) 0.005 m^3

Step 2 : Enter Research Cement Consumption

		Enter cement consumed				
Cement Consumed in Research	1	250	kg/m^3	=	1.25	kg
	2	275	kg/m^3	=	1.38	kg
	3	350	kg/m^3	=	1.75	kg
	4	400	kg/m^3	=	2.00	kg
Cement Consumed in Other Research	1	455	kg/m^3	=	2.28	kg
	2	586	kg/m^3	=	2.93	kg
	3	648	kg/m^3	=	3.24	kg
	4	750	kg/m^3	=	3.75	kg

Step 3 : Enter values to determine no. of samples for every series

No. of testing days for mix samples	(Enter Value)	=	3	days
No. of mix samples required for each testing days	(Enter Value)	=	3	mixes
	TOTAL	=	**9**	samples
No. of sets for each series	(Enter Value)	=	3	series
	TOTAL	=	**27**	samples for every series

Total Cement Consumed in each Mix Series / **Converting kg to Tonne**

	kg	kg		Tonne	Tonne
1	33.75	61.43	1	0.03	0.06
2	37.13	79.11	2	0.04	0.08
3	47.25	87.48	3	0.05	0.09
4	54.00	101.25	4	0.05	0.10

Your Cement Consumption & Carbon Dioxide Emission are discovered !!! The Values are as shown:

	Tonne	Tonne		kg	kg
1	0.034	0.06	1	33.75	61.43
2	0.037	0.08	2	37.13	79.11
3	0.047	0.09	3	47.25	87.48
4	0.054	0.10	4	54.00	101.25

The total cement consumed & CO_2 emission from Research Study : 172.13 **kg**

The total cement consumed & CO_2 emission from Other Research : 329.27 **kg**

% Difference >>> **47.72** %

CONGRATULATIONS !!!! CONGRATULATIONS !!!

You have helped to save cement consumption & CO2 emission by >> **48** %

HAPPY SAVING & HAVE A GREAT DAY !!! :):)

R4: F. de-Larrard and R. Le-Roy (1992).

THE DEVELOPMENT OF HIGH PERFORMANCE ECO-GREEN CONCRETE MIXES

Cement Consumption cum Carbon Dioxide (CO2) Emission Calculation Worksheet

Prepared by : Foong Kah Yen (Cheryl) Checked by : Assoc Prof. Dr. Nasir Shafiq July 2009

Welcome !!! Welcome !!!

START CALCULATING YOUR CO2 EMISSION & SEE HOW MUCH YOU CAN SAVE

Step 1 : Enter mix sample volumes.

Volume of mix samples (Enter Value) 0.005 m^3

Step 2 : Enter Research Cement Consumption

		Enter cement consumed				
Cement Consumed in Research	1	250	kg/m^3	=	1.25	kg
	2	275	kg/m^3	=	1.38	kg
	3	350	kg/m^3	=	1.75	kg
	4	400	kg/m^3	=	2.00	kg
Cement Consumed in Other Research	1	412	kg/m^3	=	2.06	kg
	2	422	kg/m^3	=	2.11	kg
	3	426	kg/m^3	=	2.13	kg
	4	600	kg/m^3	=	3.00	kg

Step 3 : Enter values to determine no. of samples for every series

No. of testing days for mix samples	(Enter Value)	=	3	days
No. of mix samples required for each testing days	(Enter Value)	=	3	mixes
	TOTAL	=	**9**	samples
No. of sets for each series	(Enter Value)	=	3	series
	TOTAL	=	**27**	samples for every series

Total Cement Consumed in each Mix Series / **Converting kg to Tonne**

	kg	kg		Tonne	Tonne
1	33.75	55.62	1	0.03	0.06
2	37.13	56.97	2	0.04	0.06
3	47.25	57.51	3	0.05	0.06
4	54.00	81.00	4	0.05	0.08

Your Cement Consumption & Carbon Dioxide Emission are discovered !!! The Values are as shown:

	Tonne	Tonne		kg	kg
1	0.034	0.06	1	33.75	55.62
2	0.037	0.06	2	37.13	56.97
3	0.047	0.06	3	47.25	57.51
4	0.054	0.08	4	54.00	81.00

The total cement consumed & CO_2 emission from Research Study : 172.13 **kg**

The total cement consumed & CO_2 emission from Other Research : 251.10 **kg**

% Difference >>> **31.45** %

CONGRATULATIONS !!!! CONGRATULATIONS !!!

You have helped to save cement consumption & CO2 emission by >> **31** %

HAPPY SAVING & HAVE A GREAT DAY !!! :):)

R5: G.G. Carette and V.M. Malhotra (1992).

THE DEVELOPMENT OF HIGH PERFORMANCE
ECO-GREEN CONCRETE MIXES

Cement Consumption cum Carbon Dioxide (CO2) Emission Calculation Worksheet

Prepared by : Foong Kah Yen (Cheryl) Checked by : Assoc Prof. Dr. Nasir Shafiq July 2009

Welcome !!! Welcome !!!

START CALCULATING YOUR CO2 EMISSION & SEE HOW MUCH YOU CAN SAVE

Step 1 : Enter mix sample volumes.

Volume of mix samples (Enter Value) 0.005 m^3

Step 2 : Enter Research Cement Consumption

		Enter cement consumed				
Cement Consumed in Research	1	250	kg/m^3	=	1.25	kg
	2	275	kg/m^3	=	1.38	kg
	3	350	kg/m^3	=	1.75	kg
	4	400	kg/m^3	=	2.00	kg
Cement Consumed in Other Research	1	410	kg/m^3	=	2.05	kg
	2	478	kg/m^3	=	2.39	kg
	3	524	kg/m^3	=	2.62	kg
	4	650	kg/m^3	=	3.25	kg

Step 3 : Enter values to determine no. of samples for every series

No. of testing days for mix samples	(Enter Value)	=	3	days
No. of mix samples required for each testing days	(Enter Value)	=	3	mixes
	TOTAL	=	**9**	samples
No. of sets for each series	(Enter Value)	=	3	series
	TOTAL	=	**27**	samples for every series

Total Cement Consumed in each Mix Series / **Converting kg to Tonne**

	kg	kg		Tonne	Tonne
1	33.75	55.35	1	0.03	0.06
2	37.13	64.53	2	0.04	0.06
3	47.25	70.74	3	0.05	0.07
4	54.00	87.75	4	0.05	0.09

Your Cement Consumption & Carbon Dioxide Emission are discovered !!! The Values are as shown:

	Tonne	Tonne		kg	kg
1	0.034	0.06	1	33.75	55.35
2	0.037	0.06	2	37.13	64.53
3	0.047	0.07	3	47.25	70.74
4	0.054	0.09	4	54.00	87.75

The total cement consumed & CO_2 emission from Research Study : 172.13 **kg**

The total cement consumed & CO_2 emission from Other Research : 278.37 **kg**

% Difference >>> **38.17** %

CONGRATULATIONS !!!! CONGRATULATIONS !!!

You have helped to save cement consumption & CO2 emission by >> **38** %

HAPPY SAVING & HAVE A GREAT DAY !!! :):)

APPENDIX D

SAMPLE OF ENERGY EFFICIENCY WORKSHEET

THE DEVELOPMENT OF HIGH PERFORMANCE ECO-GREEN CONCRETE MIXES

Energy Consumption During Production Calculation Worksheet

Prepared by: Foong Kah Yen (Cheryl) Checked by: Assoc.Prof. Dr. Nasir Shafiq July 2009

A. Begin the calculation for the mix series conducted

Mix series conducted with reference with Energy Chart :

CONCRETE PROPERTIES	kwh/m³	kwh/tonne
Cement (250-500 kg/m³)	330-660	137-275
Aggregate (1750-1950 kg/m³)	20	8
Production in Handling Concrete	90	37
TOTAL	440-770	182-320

Paulo Monteiro (2008)

Enter the cement content of mix series conducted in Laboratory

1	250	kg / m³
2	275	kg / m³
3	350	kg / m³
4	400	kg / m³

Total energy consumed during production:

1	440	kwh / m³	182	kwh/Tonne
2	473	kwh / m³	196	kwh/Tonne
3	572	kwh / m³	237	kwh/Tonne
4	638	kwh / m³	264	kwh/Tonne

B. With Comparison with other Research

Please state the Researcher that you want to compare with: **Alexander and Magee (2001)**

Calculations are done based on the Energy Chart

Formulaes used are based on the Energy Chart

Comparison between researchers are conducted to see the potential and the efficiency of mixes conducted via laboratory test

Enter the cement content of mixes conducted

1	315	kg / m³
2	360	kg / m³
3	410	kg / m³
4	500	kg / m³

Total energy consumed during production :

1	526	kwh / m³	218	kwh/Tonne
2	585	kwh / m³	242	kwh/Tonne
3	651	kwh / m³	270	kwh/Tonne
4	770	kwh / m³	319	kwh/Tonne

How much of energy during production is saved ???

% of energy saved during production

	kwh / m³		kwh/Tonne	
1	16	%	16	%
2	19	%	19	%
3	12	%	12	%
4	17	%	17	%

Global Energy Saving **(Trillion Tonne KWH/Year)**

1	6
2	8
3	6
4	9

SAVE ENERGY !!!

Are the mixes conducted **'Energy Efficient'** in consumption during production ???

1	YES
2	YES
3	YES
4	YES

CONGRATULATIONS !!!
YOU HAVE HELPED TO CONSERVE EARTH'S ENERGY

APPENDIX E

STANDARD ENERGY CONSUMPTION TABLE FOR CONCRETE DURING PRODUCTION (PAULO MONTEIRO, 2008)

CONCRETE PROPERTIES	kwh/m^3	kwh/tonne
Cement ($250-500\ kg/m^3$)	330-660	137-275
Aggregate ($1750-1950\ kg/m^3$)	20	8
Production in Handling Concrete	90	37
TOTAL	**440-770**	**182-320**

APPENDIX F

LIST OF EXHIBITIONS, AWARDS, PAPERS & PUBLICATIONS

Gold medal, 'ECOcrete', Open Innovation Challenge (Civil Engineering) Category, *Engineering Design Exhibition (EDX23),* Jan., 2009, Universiti Teknologi PETRONAS (UTP), Bandar Seri Iskandar, Perak, Malaysia.

Silver medal, 'ECOcrete'-Concrete with High Cement Efficiency, Low Energy Consumption and Cost Effective, Postgraduate Research Project, *Engineering Design Exhibition (EDX24),* Jul., 2009, Universiti Teknologi PETRONAS (UTP), Bandar Seri Iskandar, Perak, Malaysia.

Silver medal, 'Du*f*rete'- Concrete with High Cement Efficiency and High Durability, Postgraduate Research Project, *Engineering Design Exhibition (EDX25),* Jan., 2010, Universiti Teknologi PETRONAS (UTP), Bandar Seri Iskandar, Perak, Malaysia.

K.Y. Foong and N. Shafiq (2010). 'ECOcrete'-Concrete with High Cement Efficiency and Low Energy Consumption. *The International Conference on Sustainable Buildings and Infrastructures (ICSBI2010),* Kuala Lumpur Convention Centre, Kuala Lumpur, Malaysia.

K.Y. Foong and N. Shafiq (2010). 'ECOcrete'–Concrete with High Cement Efficiency, Low Energy Consumption and High Durability. *World Engineering Congress (WEC2010)*, Kuching, Sarawak, Malaysia.

K.Y. Foong and N. Shafiq (2010). 'ECOcrete'-Concrete with High Cement Efficiency and Low Energy Consumption, *Journal of Material Science and Engineering (JMSE)*, California, USA. (to be published)

K.Y. Foong and N. Shafiq (2010). The Development of High Performance Eco-Green Concrete Mixes, *International Conference in Postgraduate Education (ICPE 4)*, Cititel Hotel Midvalley Megamall, Kuala Lumpur, Malaysia.

APPENDIX G

DETAILS OF RESEARCH WORKS

Concrete Properties	Test Type	Standards	Testing Age (Days)	Sample Size	No. of Samples	Measurement Units
A. PHYSICAL PROPERTIES OF AGGREGATES	Sieve Analysis	BS 882: 1992 BS 812-103:1985 BS 812-103.2:1989	None	Gravels (20mm) Sand	each series	% passing
B. PHYSICAL PROPERTIES OF OPC & SF	XRF	None	28	powdered	one	%
	XRD	None	28	powdered	one	%
C. FRESH CONCRETE	Slump Test	BS EN 12350-2:2000	Fresh Concrete	None	each series & types	mm
	Mixing & Sampling	BS 1881-125:1986	Fresh Concrete		each series & types	
	Compressive Strength	BS EN 12390-3:2002 BS 1881-116:1983	3,7,28,56,120	150 mm³	3 cubes/mix/age	MPa
D. HARDENED CONCRETE	Porosity	Shafiq et.al (2007)	3,7,28,56,120	40 mm ø, 5 mm	3 cores/mix/age	%
	Tensile Strength	BS EN 12390-6:2002 ASTM C39-86: 1986	28,180	Cylinders 100 mm ø, 200 mm	2 cylinders/mix/age	MPa
	Chloride Migration	Shafiq et.al (2007)	28,120,180	100 mm³ cubes	4 parts/cube/mix	mm, %
	Modulus of Elasticity	ASTM C469-02el: 1986 BS 1881-209: 1990 BS 1881-118:1989 BS 1881-121:1983 BS 1881-109:1989	28,180	Beams 500 x 100 x 100 mm	2 beams/mix/age	GPa